PNNL-19002

Prepared for the
U.S. Nuclear Regulatory Commission
under an Interagency Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

Grain Structure Identification and Casting Parameters of Austenitic Stainless Steel (CASS) Piping

CO Ruud
AA Diaz
MT Anderson

November 2009

Pacific Northwest
NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

PACIFIC NORTHWEST NATIONAL LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Grain Structure Identification and Casting Parameters for Austenitic Stainless Steel (CASS) Piping

CO Ruud
AA Diaz
MT Anderson

November 2009

Prepared for
U.S. Nuclear Regulatory Commission
under an Interagency Agreement
with the U.S. Department of Energy
Contract DE-AC05-76RL01830

Pacific Northwest National Laboratory
Richland, Washington 99352

Summary

Inservice inspection (ISI) requirements dictate that piping welds in the primary pressure boundary of light-water reactors (LWRs) be subject to a volumetric examination based on the rules contained within the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI. The volumetric examination may be either radiographic (RT) or ultrasonic (UT) but local radiation environments and access limitations may prevent the use of the former. The purpose of the inspection is the reliable detection and accurate sizing of any service-induced degradation and/or material flaws introduced during fabrication. However, the characteristic and varied metallurgical grain structures of cast austenitic stainless steel (CASS) piping, including statically cast stainless steel (SCSS) and centrifugally cast stainless steel (CCSS), introduce significant variations in the propagation and attenuation of ultrasonic sound fields. These variations complicate interpretation of the UT responses and compromise the reliability of UT inspection.

The objective for this effort was to initiate development of the theoretical and practical information needed to understand and potentially catalog grain structures of CASS piping based on variables associated with the casting processes.

This investigation was concerned with identifying process parameters and their resultant impact on grain structures in LWR CASS piping, including small-diameter piping (i.e., PZR surge line and varied safe ends) and large-diameter primary coolant piping. The investigation began by developing a theoretical understanding of both the centrifugal and static casting processes and the major and minor parameters that affect the grain structure in these castings. Concurrently, industry, government, and academic contacts cognizant of current and past pipe casting processes were developed. These contacts were used to obtain information from LWR fabricators and CASS foundries to determine typical casting practices used and variations in those practices. In this investigation, four foundries were visited and their current and past practices were documented.

It was concluded that columnar grains and banding (layers of significantly different grain structures) were common in austenitic steels and that such an array of parameters affected their development that control of these casting variables required extraordinary effort. Further, the grain structure cast by a foundry can vary from heat to heat; and within a heat (pipe or component) from one location to another. The limited amount of information on CASS components relating foundry and heat number to specific grain structures diluted the firmness of the conclusions that could be drawn. The propensity for the development of columnar grains in CASS piping and related components may be enhanced by low ferrite content of the cast alloy.

Acknowledgments

Dr. Robert Voigt of the Pennsylvania State University and Mr. Richard D. Rishel of WESDYNE have been of invaluable help in identifying foundries and cast pipe specimen sources. Also, Dr. Steve Doctor's knowledge of the history of many of the specimens identified in this report was vital. The author's are grateful to Chris Oldfather, Senior Metallurgist at ESCO's Portland, Oregon, facility and Sr. Sales Engineer Gerry Craft at US Pipe and Foundry's Union City, California, facility, who were excellent hosts and spent a great deal of time providing historical information and technical details associated with our mission. Finally, the authors wish to thank Kay Hass at PNNL for her significant efforts in compiling, editing, and formatting this document through its evolution.

Acronyms and Abbreviations

ACE	Alloy Casting Institute
AISI	American Iron and Steel Institute
ANL	Argonne National Laboratory
AOD	argon-oxygen decarburization
APE	pipe-to-elbow (auto weld)
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
BCC	body centered cubic
CARRE	Cast Austenitic Round Robin Exercise
CASS	cast austenitic stainless steel
CCSS	centrifugally cast stainless steel
CEGB	Central Electricity Generating Board
EPRI	Electric Power Research Institute
FAM	French Foundry
FCC	face centered cubic
GFN	grain fineness number
ID	inner diameter
INE	inlet nozzle-to-elbow
IPD	Industrial Products Division
ISI	inservice inspection
LD	large diameter
LWR	light-water reactor
MD	moderately defined
MG	mixed grains
MPE	pipe-to-elbow (manual weld)
Mwe	megawatts electric
NRC	U.S. Nuclear Regulatory Commission
OD	outer diameter
ONP	outlet nozzle-to-pipe
OPE	outlet pipe-to-elbow
PD	poorly defined
PIRR	Piping Inspection Round Robin
PISC	Programme for Inspection of Steel Components
PNNL	Pacific Northwest National Laboratory
POP	pump outlet-to-pipe
PZR	pressurizer

RCL	reactor coolant loop
RRT	round robin test
RT	radiographic testing
SCC	stress corrosion cracking
SCSS	statically cast stainless steel
SFM	Sandusky Foundry and Machine
SwRI	Southwest Research Institute
UNK	unknown
UNS	Universal Numbering System
USP	U. S. Pipe
UT	ultrasonic testing
WO	well organized
WOG	Westinghouse Owners Group
WSS	wrought stainless steel

Contents

Figures

Tables

1.0 Introduction

Inservice inspection (ISI) requirements dictate that piping welds in the primary pressure boundary of light-water reactors (LWRs) be subjected to a volumetric examination based on the rules contained within the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, Section XI. The volumetric examination may be either radiographic (RT) or ultrasonic (UT) but local radiation environments and access limitations may prevent the use of the former. The purpose of the inspection is the reliable detection and accurate sizing of the service-induced degradation and/or material flaws introduced during fabrication. However, the characteristic and varied metallurgical macrostructures and microstructures of cast austenitic stainless steel (CASS) piping and fittings, including statically cast stainless steel (SCSS) and centrifugally cast stainless steel (CCSS), introduce significant variations in the propagation and attenuation of ultrasonic sound fields. These variations complicate interpretation of the UT responses and compromise the reliability of UT inspections.

To develop more accurate procedures for the UT inspection of primary pressure boundary LWR welds in CASS pipe, typical and/or generic grain structures, resulting from the casting processes used by various foundries to produce piping found in existing LWRs, needed to be identified and, if possible, catalogued.

2.0 Objective

The objective of this literature search and foundry interrogation effort is to understand the fundamental processes of casting the subject pipe and to document and collate information in the literature that is relevant to understanding the processes used and the resulting grain structures reported in various studies. Also, the literature search was to help identify organizations and individuals who might provide information as to the source and application of CASS pipe in LWRs. This report will serve to initiate development of the theoretical and practical information needed to understand and potentially catalog grain structures of CASS piping based on variables associated with the fabrication processes.

3.0 Procedure

3.1 Literature Review

Over 50 publications in the form of published papers, reports, books, and unpublished letters, memos, and emails were reviewed and are listed in Appendix A. The review was initiated with the study of several documents contained in a box given to C. O. Ruud by A. A. Diaz and these included those numbered as [1] and [2]. Others were provided by PNNL scientists, found during visits to university libraries, or were from C. O. Ruud's library; and the remainder were purchased by Pacific Northwest National Laboratory (PNNL) or obtained through the PNNL technical library. Many of the published papers were identified in the reference list of the papers reviewed. Also, the U.S. Nuclear Regulatory Commission (NRC) website, www.prc.gov-rm/doc-collections/nuregs/contract/, "Publications Prepared by NRC Contractors," was reviewed for pertinent reports.

3.2 Networking

During the literature review, several names of individuals and foundries were found, and are listed in Appendices B and C. Dr. Robert Voigt of the Pennsylvania State University and Mr. Richard D. Rishel of Westinghouse, as well as PNNL personnel, have been invaluable resources in this review.

Dr. Voigt provided a contact at ESCO, the only foundry that was identified as casting vintage SCSS components for the LWRs. The contact was John Dillon, V. P. Engineering and Technical Services, and Mr. Dillon provided the contact of Chris Oldfather, Senior Metallurgist (see Table C.1, Appendix C) at ESCO's Portland, Oregon, facility, who hosted a visit to ESCO by PNNL personnel. A summary of the visit is presented in Section 4.1.3.1.

3.3 Internet

Search of various sites on the internet led to contact with Jim Lambert, V. P. – Operational Excellence and Quality at U. S. Pipe, one of the two foundries that produced centrifugal cast pipe for the Westinghouse LWRs (see Table C.1, Appendix C). Even though U. S. Pipe no longer produces CCSS pipe, Mr. Lambert conducted a historical search and determined that they did produce CCSS pipe at their Burlington, New Jersey, foundry in the 1970s. That facility has been closed, but Mr. Lambert identified a field engineer who worked at the New Jersey foundry when LWR pipe was being cast. That field engineer was Gerry Craft, and he provided the historical information presented in Sections 4.1.2.1 and 4.1.2.2. Mr. Craft hosted PNNL personnel at the US Pipe facility in Union City, California.

Also, the internet provided a contact at Sandusky Foundry and Machine (SFM), one of the two foundries identified as producing CCSS pipe for LWRs and Delta Centrifugal (see Table C.1, Appendix C). The SFM contact was Christopher Reeve, Metallurgist (see Table C.1, Appendix C), and Mr. Reeve referred the authors to Brian Holzaephel, Director of Operations at Sandusky.

4.0 Results

Regarding the application of cast pipe in LWRs, Woo et al. (1984) and Griesbach et al. (2009) included information such as Plant Name, Number of Loops, Method of Pipe Manufacture (Forged or Cast), Pipe Material (SA-351-SF8A or SA-351-CF8M), Pipe Wall Thickness and Commercial Operation (Dates). Table 4.1 lists only cast pipe that was extracted from these reports.

Table 4.1. Information on CASS Reactor Coolant Loops (RCLs) for Westinghouse PWR plants in the United States (Woo et al. 1984; Griesbach et al. 2009)

Plant Name	Size (Mwe*)	System Loops	Pipe Material (SA-351-)	Pipe Wall Thickness**	Commercial Operation (Mo/Yr)
Kewaunee	560	2	CF8M	C	6/74
Prairie Island 2	530	2	CF8M	Unknown	Unknown
D. C. Cook 1	1090	4	CF8M	B	8/75
Farley 1	829	3	CF8A	B	12/77
D. C. Cook 2	1054	4	CF8M	C	7/78
North Anna 1	934	3	CF8A	A	6/78
Beaver Valley 1	852	3	CF8M	C	4/77
North Anna 2	788	3	CF8A	A	12/80
Farley 2	829	3	CF8A	B	7/81
McGuire 1	1180	4	CF8A	B	12/81
Sequoyah 1	1140	4	CF8M	B	7/81
Sequoyah 2	1140	4	CF8M	B	6/82
McGuire 2	1180	4	CF8A	B	10/83
Callaway 1	1157	4	CF8A	B	?/85
Catawba 1	1153	4	CF8A	B	?/85
Wolf Creek	1158	4	CF8A	B	?/84
Beaver Valley 2	852	3	CF8A	C	?/86
Vogtle 1	1113	4	CF8A	B	?/87
Vogtle 2	1113	4	CF8A	B	?/88
Comanche Peak 1	1150	4	CF8A	B	?/84
Millstone 3	1150	4	CF8A	B	?/86
Catawba 2	1153	4	CF8A	B	?/85
Watts Bar 1	1177	4	CF8A	B	?/84
Watts Bar 2	1177	4	CF8A	B	?/85
South Texas 1	1250	4	CF8A	B	?/86
South Texas 2	1250	4	CF8A	B	?/87

*Mwe = megawatts electric
** A hot leg = 2.33 in., crossover leg = 2.48 in., cold leg = 2.21 in.
B hot leg = 2.45 in., crossover leg = 2.60 in., cold leg = 2.32 in.
C hot leg = 2.47 in., crossover leg = 2.59 in., cold leg = 2.47 in.

Also, the data shown in Table 4.2 were reported at the ASME Section XI Task Group Meeting in San Francisco, California, on August 4, 2008, regarding American Society for Testing and Materials (ASTM) A351 CF8M alloy used in Westinghouse-designed plants (Griesbach et al. 2007). Cast austenitic stainless steel pipe was incorporated in Westinghouse plants of 2, 3, and 4 loop designs as indicated in the following list. Note that Table 4.1 lists seven plants with CF8M and Table 4.2 lists only six.

Table 4.2. ASTM A351-CF8M CASS Piping Incorporated in Westinghouse Plants According to Griesbach et al. (2007)

No. of Loops	No. of Plants	No. with CASS Pipe	No. with CF8M
2	6	2	2
3	16	6	1
4	29	18	3

Griesbach also referenced the Westinghouse data included in Appendix E of this report. That data resulted from a sampling survey conducted by WESDYNE (a Westinghouse NDE Company) in which 70 heats of cast pipe and 70 heats of cast fittings (elbows) were sampled (surveyed). This included about 20 Westinghouse power plants and the material samples were from the primary loop cast piping and fittings. The survey concentrated on CF8, CF8A, and CF8M materials. Test data included both mechanical and chemical properties as well as delta ferrite content (see Appendix E). The sources of the cast pipe were U. S. Pipe and Foundry, Inc. and Sandusky Foundry and Machine Company, and the fittings (elbows) were all cast by ESCO except one elbow from an Italian foundry.

4.1 Process Description and Parameters

4.1.1 Introduction

Metal casting is a process in which molten metal is caused to flow into a mold where it solidifies into the desired shape, for this study that shape is a pipe (tube) or a shape connected to a pipe such as an elbow, a safe end, or nozzle. The mold is a cavity that is of suitable shape and size to produce a solid casting of the desired shape and size. In most cases, the mold is larger than the desired casting to account for shrinkage occurring upon solidification and cooling.

There are many casting processes and they are designated by the type of mold, or molding process, used (AFS 1957; ASM 1992; Groover 2004). There are two major categories of molding, or casting, processes. These are expendable and permanent molds. With the former, the molds are destroyed in the casting process after the metal solidifies. In the latter, the casting is extracted from the mold and the mold is used again. Of the processes relevant to this study, centrifugal and static casting, the former is a permanent mold process and the latter could be either a permanent mold with a expendable core or an entirely expendable mold, that is, sand molds (Groover 2004), process.

The process steps for all casting processes include: mold fabrication or preparation, melting and alloying, pouring, solidification and cooling, and extraction of the casting from the mold.

4.1.2 Centrifugal Cast Stainless Steel

Centrifugal casting is commonly a permanent mold process where the mold can be used many times. An excellent description of the history of centrifugal casting processes and equipment is provided by Cumberland (1963) and he mentions that the important parameters are temperature, pouring rates, rotational speed, and mold coating practice as well as composition.

A brief description of centrifugal casting and the three basic types (groups)—1) true centrifugal casting, 2) semi-centrifugal casting, and 3) centrifuge casting—is found in Groover (2004). According to Groover, "In true centrifugal casting, molten metal is poured into a rotating mold to produce a tubular part. Examples of parts made by the process include pipes, tubes, bushings and rings. Typically for pipes (tubes) molten metal is poured into a horizontal rotating mold from one end. In some operations mold rotation commences after pouring has occurred rather than beforehand. The high speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. Thus, the outside shape of the casting can be round, octagonal, hexagonal, and so on. However, the inside of the casting is (theoretically) perfectly round due to the radially symmetric forces at work."

Royer (1987) describes a horizontal centrifugal casting machine as consisting of four parts:

- the shell (mold)
- the casting spout
- the roller tracks
- the end heads

Hall (1948b) states than in practice, pouring rate, metal temperature, and rotational speed for centrifugal casting are determined experimentally.

Based on the processing steps mentioned in the previous section; i.e.,

- mold fabrication or preparation,
- melting and alloying, pouring,
- solidification and cooling, and
- extraction of the casting from the mold,

the following parameters, plus rotation, are important in centrifugal casting (ASM 1992).

<u>Mold Fabrication or Preparation</u> – Common mold materials are listed as steel, copper, and graphite although the permanent mold for CCSS pipe is likely a cast iron or steel cylinder (ASM 1992). Steel or cast iron molds are used with various types of coatings to prevent adhesion of the casting to the mold, for protection of the mold, and ease of stripping the casting from the mold. Coatings range from refractory slurries to dry powdered dressings containing graphite, ferrosilicon, etc. (ASM 1992; Groover 2004) to rammed sand linings. Beeley (1972) writes, "For production of tubular castings in a wide range of alloys, metal distribution is achieved by use of a metal die provided with a refractory and insulating coating of rough texture."

Coatings may be applied to the heated bore surface of the rotating die through a spray head at the end of a lance mounted on a reciprocating carriage; and would likely show a controlled roughness when dried. Cumberland (1963) also mentioned that application of a refractory coating to the metal mold allowed casting of more difficult alloys in longer lengths. This allowance would also apply to rammed sand linings. Cumberland also notes that by spraying a slurry on to the heated mold, a thin layer of refractory with a stippled surface is obtained, which provides resistance (friction), or tooth, to the movement of the contacting molten metal. This resistance exerts a braking action on the axial flow of the molten metal and presumably provides traction to accelerate the molten metal to the rotational speed in the circumferential direction (Cumberland 1963).

Melting and Alloying – The most common alloys of austenitic stainless steel (sometimes referred to as 18-8 steels) used in cast pipe for LWRs is approximately compositionally equivalent to AISI 304 or 316 wrought alloys. Designations include ASTM A351 (CA-6NM, 12Cr-4Ni-0.7Mo, UNS J91540), ACI CF-3 (19Cr-10Ni, UNS J92700), ACI CF-8 and CF-8M (19Cr-9Ni), UNS J92600). The acronyms include American Iron and Steel Institute (AISI), American Society of Testing Materials (ASTM), Alloy Casting Institute (ACI), and Universal Numbering System (UNS) (ASM 1979; Chopra and Chung 1985; Anderson et al. 2007). The melting temperatures are approximately 2700°F (1480°C), 2650°F (1455°C), and 2600°F (1425°C), respectively, for A351, CF-3, CF-8 and CF8M. The temperature difference between the liquidus and solidus for 18-8 stainless steels is about 88°C according to Figure 1 in Lundin and Chou (1983).

The composition ranges and limits for AISI 304L, 304 and 316 stainless steels are as follows (ASM 1980):

AISA Alloy	ASTM A351	C max	Mn max	Si max	P max	S max	Cr	Ni	Mo
304L	CF3	0.03	1.50	2.00	0.04	0.04	17.0–21.0	8.0–12.0	N/A
304	CF8&8A	0.08	1.50	2.00	0.04	0.04	18.0–21.0	8.0–11.0	N/A
316	CF8M	0.08	1.50	2.00	0.04	0.04	18.0–21.0	8.0–12.0	2.0–3.0

Note that according to the ASM Handbook, page 96, ferrite (delta) content is controlled by composition, and chromium, molybdenum and silicon promote its formation (ASM 1980).

Pouring – The pouring process and temperature affect the structure of the resultant centrifugal casting more than the initial mold temperature (ASM 1992). “Molten metal can be introduced into the mold at one end, at both ends, or through a channel of variable length. Pouring rates vary widely according to the size of the casting being produced and the metal being poured.” Davis (1973) mentions the DeLevaud process of horizontal centrifugal casting where, “The pouring spout is traversed parallel to the axis of rotation and the thickness of the casting is determined by the rate of feeding.” It must be recognized that during the pouring process the direction of movement of the molten metal changes from vertical to horizontal (Hall 1948c). Beeley (1972) notes that in pouring horizontal castings the metal stream is generally directed against the downward moving side of the mold, allowing a maximum opportunity for the metal to acquire angular momentum before passing the lowest point of rotation.

The degree of superheat required to produce a centrifugal casting is a function of the alloy being poured, mold size, and physical properties of the mold material (ASM 1992). The following empirical formula was given as a guideline to calculate the degree of superheat needed for centrifugal casting: $L = 2.4\,\Delta T + 110$ (degrees C), where L is the length of spiral fluidity (in mm) and ΔT is the degree of superheat (in degrees C). (Note: No definition of spiral fluidity was found in the literature search.) The use of this equation for ferrous alloys results in casting temperatures that are 50 to 100°C above the liquidus temperature (ASM 1992). Cumberland (1963) suggests that 20 to 80°C above the solidus is optimum; however, that would be lower than suggested by the equation because the liquidus is typically about 88°C higher than the solidus in cast austenitic stainless steel (Lundin and Chou 1983).

Rate of Rotation – ASM (1992) states, "As the molten metal enters the mold, a pressure gradient is established across the tube (wall) thickness by centrifugal acceleration. This causes alloy constituent of various densities to separate, with lighter particles such as slags and nonmetallic impurities gathering at the inner diameter. The thickness of these impurity bands is usually limited to a few millimeters, and they are easily removable by machining."

Theoretically, it is only necessary for the molten metal to be caused to rotate at a speed sufficient to generate a centrifugal force equal to that of gravity. However, in practice, it is always necessary to use higher speeds because slip occurs between the melt and mold (or solidified) surface. There is a dependence of rotation on pouring rate in that the faster the metal is introduced into the mold, the faster the mold must turn to keep the molten pool against the solidifying metal. Also, factors such as friction, surface tension, inertia, etc. affect the rotational velocity of the molten metal, and thus, it is not possible to calculate the ideal rotational speed of the mold (Hall 1948a; Cumberland 1963).

Nevertheless, Groover (2004) offers the following equation to calculate the rotational speed with a G-factor of 65 times the force of gravity:

$$\text{Rotational Speed} = N = 9.5\,(2gGF/D)^{1/2},$$

where $g = 32.2\ \text{ft/sec}^2$,
GF = Gravity factor $= (D(\pi N/30)^2)/2g$,
D = Inner diameter (ID) of the mold (outer diameter [OD] of the CCSS pipe) in feet.

Thus, according to the equation, the speeds of rotation for 30.5-cm (12-in.), 60.0-cm (24-in.), and 91.4-cm (36-in.) OD pipes would be approximately 617, 440, and 357 rpm, respectively to generate a G factor of 65.

In casting of pipes, as the pipe wall thickens, the diameter of the solid metal deceases, necessitating a higher rotational speed to maintain the same centrifugal force (Hall 1948a). Usually the speed of rotation is varied during the casting process and the cycle can be divided into three parts:

- At the time of pouring, the mold is rotating at a speed sufficient to throw the molten metal against the mold wall.
- As the metal reaches the opposite end of the mold, the speed of rotation is increased.
- Speed of rotation is held constant for a time after pouring; the time at constant speed varies with mold type, metal being cast, and required wall thickness (Cumberland 1963; ASM 1992).

The ideal speed of rotation causes rapid adhesion of the molten metal to the mold wall with minimal vibration. Such conditions tend to result in a casting with a uniform structure (continuous columnar grains through the wall thickness). Too slow a speed of rotation can cause sliding and result in poor surface finish. Too high a speed of rotation can generate vibrations, which can result in circumferential segregation banding (Davis 1973). Nevertheless, high rotational speeds are frequently advised to minimize bore shrinkage, either to help the molten metal to penetrate the inter-columnar cavities, or to promote the movement of grains forming near the bore to move outwards (Cumberland 1963).

Solidification and Cooling – Cast austenitic stainless steels are considered duplex stainless steels and, having high chromium content, initially solidify as a primary delta phase according to the constant Cr pseudobinary Fe-Ni phase diagram. During cooling and in the solid state, when gamma- (austenite-) like elemental concentrations (mainly C and N) are sufficient, some solid-state transformation of delta to gamma occurs, diminishing the delta ferrite content (Massoud et al. 1998). Also, columnar grains may develop at the center of a section due to nickel enrichment of the liquidus.

Several parameters influence solidification:

- The mold, including mold material, its thickness, and initial mold temperature.
- The thickness and thermal conductivity of the mold wash or lining used.
- Casting conditions, including the pouring process, pouring temperature, pouring rate, and speed of rotation.
- Any vibrations present in the casting system.

The parameters with the greatest effect on solidification and cooling, with a given pouring process, are the pouring temperature of the molten metal and the thickness of the mold wash or lining employed (ASM 1992).

Extraction of the Casting from the Mold – The casting shrinks away from the ID of the mold upon solidification and cooling, thereby allowing for ease of extraction. Flinn (1963), in regard to horizontal centrifugal casting, mentioned that when refractory-coated permanent molds are used, the casting can be ejected from the mold by a piston.

Post-Heat Treatment – If the cooling rate between 900° and 600°C (1650° and 1110°F) is sufficiently slow, delta ferrite can transform to a brittle sigma phase, resulting in a degradation of mechanical properties and M23C6 carbides may precipitate at the delta/gamma interfaces. Therefore, post-heat treatment (around 1000°C, 1850°F) followed by a rapid cool is usually required (Massoud et al. 1998).

4.1.2.1 U. S. Pipe Process According to Email of 09/10/08

As a part of the investigation of CCSS casting processes for LWR application, it was necessary to learn about the specific processes used. Thus, an internet search led to Jim Lambert, V. P. – Operational Excellence and Quality at U. S. Pipe. The following historical notes regarding the casting of CCSS at U. S. Pipe in the 1960s and 1970s were offered by Gerry Craft, Regional Sales Engineer (see Table C.1, Appendix C, and the email of September 18, 2008, in Appendix F).

> I worked in [Industrial Products Division] IPD (U. S. Pipe’s Burlington, NJ facility) briefly as a co-op in 1965 when I was a Final Inspector and Assistant Radiographer, then again from 1972 to 1976 after a hitch in the Air Force. A major customer at that time was called WABCO for short. It was the Westinghouse Airbrake Company, later just Westinghouse. I recall making what we called Nuclear Reactor Coolant Piping in the IPD Steel Foundry. IPD had about 200 alloys of iron and steel in the line-up, most of it melted in motor-generator set induction furnaces, although they also had a small carbon-arc furnace for larger heats. That was mothballed during my time there.

These centrifugal castings had a target weight of about 14,000 lbs and were made of an austenitic stainless steel, as you mentioned. I seem to recall they were made of 316 SS, but I'm not sure because I remember about that same time making some castings from a more exotic 347 SS.

These were high quality castings that required 100% Liquid Penetrant Testing and 100% Radiography. They were rough machined (turned, bored, and parted) in the IPD Machine Shops before testing. In the image I have of them, they were about 33" OD by 26" ID by about 45" long with about a 3½" wall.

I do not believe these were actual coolant pipe. I think Westinghouse bought our castings and had them forged into pipe elbows or bends for the coolant piping system, which, of course, was all welded.

Understandably, these castings were considered critical parts of a nuclear power plant, so we went to great pains to make them good. In trying to cut down on the boring detail I will say that we had three sizes of horizontal spinners, small, intermediate, and large. The Westinghouse castings were made on one of two large spinners that were specially overhauled to run extremely smoothly. Prior to tap out, the mold was brought to casting speed and the set up was checked with a vibration meter. If the amplitude of vibration could not be maintained below a certain amount, the cast was aborted. I was told that excess vibration affected grain size in the casting, which in turn affected weldability.

As for the actual manufacturing process, IPD had three MG (motor-generator) sets driving induction furnaces. The two larger sets normally had one 4,000 lb and one 2,000 lb furnace each, but the 4,000 lb could be swapped out for a 5,000 lb unit if required. The smaller MG set normally had two 1,000 lb furnaces. The range of casting size ran from about 30 lbs up to a maximum of about 17,000 lbs. (This was done by combining the heats from all six furnaces into one bull ladle, or occasionally two which were poured simultaneously from each end of the mold.) Pouring temperature for a large 300-series stainless steel alloy would have been around 2750°F. (Author's Note: the melting temperature for CF8 and CF8M, AISI 316, is about 2600°F.)

All of the tubular or roll products were "flat-cast," meaning the molds were level horizontally, not pitched like a DeLavaud casting machine (see Section 4.1.2 under Pouring in this report). Metal was poured into the mold through a "horn gate" which was like a funnel with a curved spout. This means that the metal had to run down the whole length of the mold instead of being laid in a ribbon as is done using a trough on a DeLavaud machine." (Author's note: Under these pouring conditions the molten metal at the pouring location would have been at a higher temperature than the molten metal at the farthest distance along the length from the pouring location. Thus, the grains at the pouring location would tend towards being large and columnar and those at the farthest distance from the spout, smaller and more equiaxed; see Section 4.2.2, Pouring Temperature and Rate of this report) (Northcott and Dickin 1944).

Heated molds were sprayed with a coating made of diatomaceous silica flour, bentonite, and water. The heat of the mold evaporated the water leaving a relatively hard "tooth" that provided traction for the molten metal. (See Section 4.1.2, Mold Fabrication or Preparation.) The mold coating was applied in multiple passes until a thickness of approximately 0.10" was achieved.

This is very like the Large Diameter Casting Process used at the Bessemer Plant. In fact, when I worked in R & D in early 1965, we made the first 48" centrifugally cast ductile iron "casting" (it was a pipe without a bell) using a stationary mold and a ladle/trough car moving on rails. This process was refined and became our LD process at Bessemer ten years later.

I suspect this is more information than you wanted or needed, but I haven't thought about this stuff in years so I figured I'd better record it while I still can. I have spoken with the last President of IPD and the last Production Control Supervisor within the last year. They are both in their late seventies. If there are any other details you might be looking for, I could call them to see what they remember."

4.1.2.2 U. S. Pipe Process According to PNNL Visit of 03/11/09

On February 18, 2009, Aaron Diaz and Clayton Ruud of PNNL visited Gerry Craft, U. S. Pipe Regional Sales Engineer (see Table C.1, Appendix C, and the email of September 18, 2008, in Appendix F) at Union City, California, and toured the foundry.

The Union City plant centrifugally casts only ductile iron pipe of various diameters up to about 36 in. The day we visited we witnessed the casting of pipe about 30 in. in diameter and 1-in. wall thickness. The Union City foundry is a high production facility and they were casting approximately 18-ft-long pipe sections about every 5 minutes. The molds were tilted at 4 to 7 degrees and the metal was laid in a ribbon as done using a trough on a DeLavaud machine (see Section 4.1.2 under Pouring).

Before we toured the foundry, we discussed and reviewed Gary Craft's recollection of the casting of austenitic stainless steel pipe in the 1970s.

The Industrial Products Division (IPD) of the U. S. Pipe Foundry in Burlington, New Jersey, closed in 1985 and was the only U. S. Pipe foundry casting austenitic pipe. As well as austenitic, IPD cast over 200 different alloys including dual-metal pipe. The U. S. Pipe heat C2291A used in the Westinghouse Owners Group (WOG) OPE-2 specimen listed later in Table 4.4 was cast in 1972 or 1973.

In our discussions we referred to the parameters listed in Section 4.1.2 of this report; that is, mold fabrication or preparation; melting and alloying, pouring; rotation: solidification and cooling; and extraction of the casting from the mold. Gerry Craft provided the following comments regarding these parameters and his recollection of the production of CASS pipe.

Regarding mold fabrication or preparation: The molds were forged AISI 4130 or 4340 alloy steel, or cast iron with the ID machined, but not to a honed finish. They ranged from about 5 to 20-ft long with a 2 to 3-in. wall thickness and their diameters depended on the pipe size to be centrifugally cast. The ID of the molds were coated with a slurry (wash) of diatomaceous flour, bentonite, and water using 80 to 100 passes in a 20–30 minute time period while the mold was spinning. After each pipe was cast and before recoating, the mold was wire brushed to remove all traces of the previous coating. This brushing left scratch marks on the mold ID. The slurry was at ambient temperature but the molds had been pre-heated to about 350° to 400°F before the slurry was sprayed. The direction of the spray nozzle affected the texture of the coating, and the coating needed to have a degree of roughness (stippled surface) to provide "tooth" (resistance) to grab the molten metal and accelerate it to the needed spin velocity (see Mold Fabrication or Preparation under Section 4.1.2). The slurry dried to an adherent coating about

0.1-in. thick soon after being sprayed and the austenitic steel was poured into the mold within an hour after the slurry was sprayed. At that time, the mold was still warm to the touch.

Regarding melting and alloying, pouring: Induction furnaces were used to melt the austenitic steel and metal was poured into the mold through a “horn gate” which was like a funnel with a curved spout. Gerry Craft stated that the induction furnace provided a very uniform melt pour composition. The exit end of the funnel was positioned such that the molten metal impacted the down travel side of the mold (see Section 4.1.2, Pouring, in this report). The molds were horizontal, not inclined as with the ductile iron pipe casting witnessed during our visit. The heats ranged from 14,000 to 17,000 pounds in size. Pouring was done from both ends but one end was started first using the “bull ladle” which was the larger of the two. The “bull ladle” constituted about 2/3 of the pour. This meant that the metal had to run down the length of the mold instead of being laid in a ribbon as is done using a trough on a DeLavaud machine. Pouring started with the “bull ladle” at one end, and pouring began slowly until the mold coating was overlaid with molten metal. Then pour rate was increased to keep the “horn gate” filled, requiring about 20 to 30 seconds. The smaller pour at the other end was initiated shortly thereafter and the entire pour only required 2 to 3 minutes. The temperature variation ranged no more than 50°F along the pipe, 2750° to 2800°F. The ladles were covered with a 1.8-in.-thick asbestos paper during pouring to maintain the temperature. A “yardstick” for a successful pour was that a thin stinger of only 5 or 10 pounds of metal solidified along the spout of the ladle. If a heavy stringer, or “skull,” was left, the pour was too cold; and if no metal was left in the ladle, the pour was too hot. The concern with temperature was that it affected the dimension of the casting; that is, too thick or thin of a wall, or led to casting defects.

Regarding rotation: The rotation rate was 200 to 300 RPM, in spite of the fact that the goal was to rotate the mold to provide 7 to 10 g’s on the ID. According to the equation under Rate of Rotation in Section 4.1.2, the rotational speed to provide 7 and 10 g’s on a 24-in. ID mold would be 143 and 171 RPM, respectively. For a 36-in. ID, this would be 117 and 140 RPM, respectively. Thus, the centrifugal force was greater than 10 g’s and this is in general agreement with the literature that suggests that forces on the order of 75 to 120 g’s are generally used (ASM 1992) (see Rate of Rotation under Section 4.1.2). The rotation was held constant throughout the pour. The 36-in. spinner RPM was 850 to 950. Note that this is the spinner speed, not necessarily the mold RPM. Extensive procedures were applied to reduce vibration to a few thousandths of an inch. Vibration was measured by touching a handheld probe against the rolling platform “frame.” A “fabrica” padding (similar to a thick tire rubber) was placed under the rolling platform frame legs that were bolted to the concrete foundry floor. Production rate was about one pipe per day because of the precise production requirements.

Regarding solidification and cooling: In order to control cooling, dry diatomaceous flour (trade name “Cellite”) was shoveled inside the cast pipe to reduce radiant heating loss and slow the cooling.

Regarding extraction: The solidified pipe was pushed out of the mold as described in Section 4.1.2, Extraction of the Casting from the Mold.

Similar casting parameters, mold temperatures, rotational speeds, mold linings, etc, were noted on a tour of the Manoir Foundry in France. This foundry was responsible for all of the CASS piping used in French reactors, and for a limited amount of primary coolant piping in the United States. The tour was part of the NRC/IRSN collaborative on CASS piping. Table 4.3 (shown later on page 4.13) provides the limited information obtained during this plant tour.

The notes from the Delta Centrifugal visit were not included in this section because Delta produced no CCSS pipe for Westinghouse LWRs. The notes from the Delta visit are provided in Appendix I.

4.1.3 Statically Cast Stainless Steel

Statically cast austenitic stainless steel safe-ends, elbows, and nozzles are likely to be cast by the green sand molding process.

The sand molding, or sand casting, process consists of pouring molten metal into a sand mold, allowing the metal to solidify, and then breaking up the mold to extract the casting. The sand mold is composed of sand particles held together with a mixture of clay and water or a resin to provide a mold with sufficient strength to withstand the hydraulic pressure of the molten metal. A core, made with sand and resin for a binder, provides the ID of the elbow, nozzle, or safe-end (ASM 1992; DeGarmo et al. 1997; Groover 2004).

Based on the processing steps mentioned in Section 4.1.1 (i.e.,

- mold fabrication or preparation,
- melting and alloying, pouring,
- solidification and cooling, and
- extraction of the casting from the mold),

the following parameters are important in static casting.

Mold Fabrication or Preparation – The sand mold is made by packing the sand-binder mixture around a pattern that is slightly larger than a full-sized model of the casting to be made. The slightly larger size is to account for solidification and thermal shrinkage. The size and shape of the mold, the type of sand, as well as the design of the sprues, gating, and riser system will affect the cooling, solidification, and grain structure of the casting (ASM 1992; DeGarmo et al. 1997; Groover 2004).

Melting and Alloying, Pouring – Alloying considerations are as described for CCSS pipe. However, to fill the mold, the molten metal is poured into a feeding system of sprues, runners, and gates cut into the sand mold (ASM 1992; DeGarmo et al. 1997; Groover 2004).

Solidification and Cooling – The cooling process is slower than for CCSS products because the sand mold is not as efficient a heat conductor as the permanent mold material; however, heat sinks (chills) are often used to enhance thermal conduction (ASM 1992; DeGarmo et al. 1997; Groover 2004). Nevertheless, CASS, considered duplex stainless steels and having a high chromium content, initially solidify as a primary delta phase according to the constant Cr pseudobinary Fe-Ni phase diagram. During cooling and in the solid state, when gamma- (austenite-) like elemental concentrations (mainly C and N) are sufficient, some solid-state transformation of delta to gamma occurs, diminishing the delta ferrite content. Equiaxed grains occur at in the center of large statically cast sand castings, whereas their surface tend towards columnar grains. However, columnar grains may develop in the center of a section of the casting due to nickel enrichment of the liquidus. The grains tend to be smaller and more elongated near the chills than near the risers where cooling is slower (Massoud et al. 1998).

Extraction of the Casting from the Mold – The heat of the molten metal tends to destroy, or at least weaken, the clay-water or resin bond between the sand particles. The casting can then be easily extracted from the broken mold (ASM 1992; DeGarmo et al. 1997; Groover 2004).

Post-Heat Treatment – If the cooling rate between 900° and 600°C (1650° and 1110°F) is slow, delta ferrite can transform to a brittle sigma phase, resulting in a degradation of mechanical properties, and $M_{23}C_6$ carbides may precipitate at the delta/gamma interfaces. Therefore, post-heat treatment around 1000°C (1850°F) for 5 to 10 hours, followed by a rapid cool, is required. This homogenizing treatment allows dissolution of the embrittling phases such as sigma and carbides that may have precipitated during solidification (Massoud et al. 1998).

4.1.3.1 ESCO Process

As a part of the investigation of SCSS casting processes for LWR application, it was important to learn about the specific processes used, thus necessitating a foundry visit to interview personnel involved in the casting processes. The only foundry identified that supplied statically cast austenitic stainless steel nozzles, safe-ends, and elbows to Westinghouse for LWRs was ESCO in Portland, Oregon. Through a contact provided by Dr. R. C. Viogt with John Dillon, ESCO-V.P. of Engineering and Technical Services, PNNL personnel were introduced to Chris Oldfather, Senior Metallurgist at ESCO. Mr. Oldfather hosted a visit and tour of the casting facilities at 2141 NW 25th Ave., Portland, Oregon, 97210-2578 on October 1, 2008, where the Westinghouse LWR pipe components (e.g., elbows, nozzles, etc.) were cast. PNNL personnel participating were Michael Watkins, Aaron Diaz, Michael Anderson, and Clayton Ruud. Following is a description of the visit and tour: The visit was initiated by meeting in a conference room with Chris Oldfather and his describing the process of static casting of large castings in sand molds.

The process used now and when the Westinghouse components were cast was not green sand molding, where the mold consists of sand particles held together with wet clay. The wet clay binds the sand particles together to provide sufficient strength to the mold to contain the molten metal until it solidifies. Instead, the mold material used was a mixture of silica (SiO2) and zircon (ZrSiO4) sand with a sodium silicate (water glass) or an organic resin binder. Also, chromite (FeCr2O4) or olivine (MgSiO4) sands may have been used. The sand was selected for the grain fineness number (GFN), which affects the surface finish quality of the casting, as well as the strength of the binder. Chromite sand molds offer the best heat transfer according to Oldfather.

Cores were used to provide the inside diameters of the static castings, and the sand binder for the cores was usually an organic resin due to its higher strength. Also, stainless steel chaplets were used to help support the core before pouring (ASM 1992). The chaplets were removed from the castings with those areas repaired by welding. The chaplets were not near the ends of the elbows and nozzles where they might be joined to pipe or other components by welding.

The present melting process for ferrous alloys at ESCO uses an arc furnace, followed with argon-oxygen decarburization (AOD) (ASM 1992). Prior to 1970, scrap metal would have been melted in an arc furnace and the melt decarburized using an oxygen lance. From 1970 to about 1975, an induction furnace would have been used for melting. Before about 1976, the carbon level would have been near the 0.08 percent maximum carbon for ASTM A351 CF3, CF8 and CF8A, but since late 1976 the application of AOD would have brought the carbon to an average of 0.03 percent. Also, a ferro-calcium-silicon alloy (CaSi) may have been added to deoxidize the melt. This CaSi may have aided in grain refinement in austenitic stainless steel, but this was never confirmed. Titanium was not used as a scavenger for nitrogen, carbon, or oxygen.

According to Chris Oldfather, the castings contained about 10 percent delta ferrite, by calculation and he stated that the pouring temperatures would have been between 2750° and 2850°F. Note that the melting temperatures are approximately 2700°F (1480°C), 2650°F (1455°C), and 2600°F (1425°C), respectively, for A351, CF-3, and CF-8 or CF8M. This implies that ESCO pouring temperatures could have been 50 to 250°F (28 to 139°C) above the melting temperature (liquidus) and higher than those suggested by Cumberland (1963), and both lower and higher than those suggested by ASM (1992) equations (see Pouring under Section 4.1.2 in this report). After pouring, the casting would have been allowed to cool for four to five days before it was broken out of the mold, with the flask having been removed a day or two after pouring to accelerate the cooling. The castings would have been near room temperature at breakout.

4.1.4 Summary of Process Parameters to Document for CASS Pipe

For a given stainless steel alloy, the following process parameters are important for documentation of the casting conditions extant when CASS pipe was cast for primary pressure boundary application of LWRs:

- Mold material and dimensions;
- Mold wash or liner material, thickness, and surface texture;
- Mold and wash or liner temperature;
- Pouring method, rate, and schedule;
- Pouring temperature and range;
- Rotation rate schedule and uncertainty; and
- Vibration schedule, amplitude, and frequency.

Table 4.3 summarizes the practices of five foundries visited during this investigation. Four of the foundries currently or previously centrifugally cast austenitic stainless steel pipe and one, ESCO, statically cast piping components such as elbows. Two of the foundries, Sandusky Foundry and Machine (SFM) and U. S. Pipe (USP), centrifugally cast pipe for Westinghouse LWRs.

Table 4.3. Foundry Practice for Cast Austenitic Stainless Steel Pipe and Components

Parameter	SCSS @ ESCO	CCSS @ U. S. Pipe	CCSS @ Delta[(a)]	CCSS @ SFM[(b)]	CCSS @ Manoir[(c)]
Mold Material	Silica & zircon sand bonded by sodium silicate	Forged low alloy steel or cast iron	Forged low alloy steel 4220 or cast iron, >16” are forged, 2.5’ to 13’ long		Forged high molybdenum steel
Mold Wash or Lining	N/A	Ceramic slurry ~0.1-in. thick	Alumina slurry ~0.06 in. thick	1 to 2 inches of rammed sand	Zirconium, silica, bentonite slurry
Mold Temp. @ Pouring	Room temperature	~150°F	~ 300°F		~400–750°F
Alloy	CF3, CF8, CF8M	CF8M	Austenitic		Austenitic
Pouring Method	N/A	Both ends, horizontal	One end, horizontal		One end
Pouring Temp.	2750–2850°F	2750–2800°F	~2800 ± 50°F, heavy wall + 50°F		Proprietary
Rotation Rate	N/A	200 to 300 RPM, constant	~100 GF @ bore, constant		Very high, several hundred GF
Vibration	N/A	A few 1/1000 inches	~ 10/1000 inches		Minimized, none is desired
Cooling Method & Schedule	Flask removed in ~ 1 to 2 days	Dry diatomaceous flour shoveled into ID	Spray cooling after pouring & before complete solidification		Externally cooled by jet-water spray for ~1 hr, casting removed ~2 Hr, ~200° F
Post Heat Treatment	2000°F & water quench	Could not recall	2050°F/hr/inch of wall		Solution anneal

(a) Not identified as casting pipe for Westinghouse LWRs.
(b) Sandusky Foundry and Machine declined the request to visit and gather information, but did report that when they cast the CCSS pipe for Westinghouse in the 1970s they used a rammed sand lining but their present practice is to use a “thin spayed refractory coating (see Appendix F email of Ftiday, October 31, 2008 from cor1 to aaron.diaz.
(c) One of the authors, Michael T. Anderson, visited Manoir Foundry in 2009 and gathered the information for this column.

4.2 Grain Structure Development

4.2.1 Introduction

Examination of CCSS materials is difficult to perform due to the coarse microstructure that characterizes these materials. The general microstructural classifications for CASS components are columnar, equiaxed, and a mixed and layered columnar-equiaxed condition of which the majority of field material is believed to be the latter. Figure 4.1 and Figure 4.2 illustrate the general classes of microstructures and the diverse variations in grain orientations, mixing, and layering.

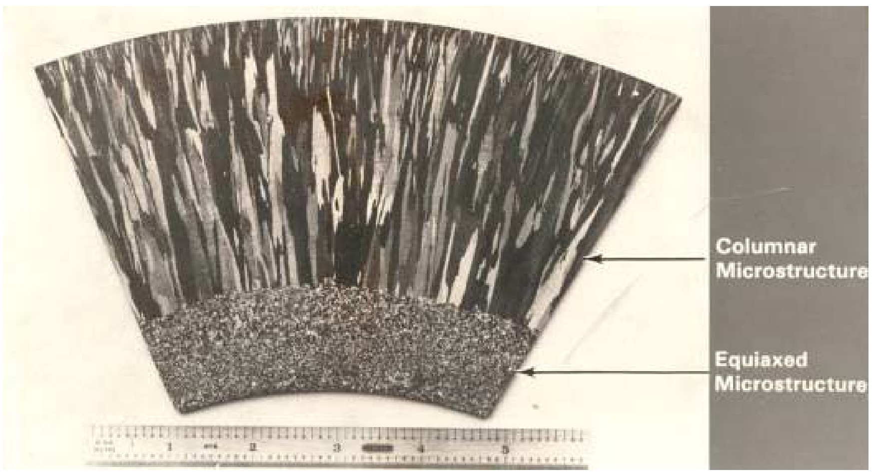


Figure 4.1. Specially Fabricated Sample Illustrating Both Columnar (dendritic) and Equiaxed Microstructures in Centrifugally Cast Stainless Steel

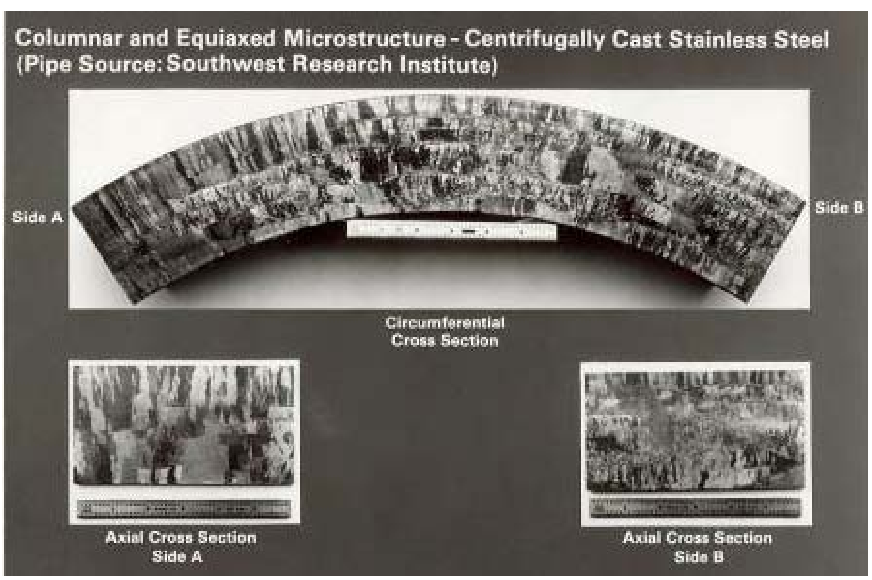


Figure 4.2. Circumferential and Axial Cross Sections of a Centrifugally Cast Stainless Steel Pipe Section Provided by Southwest Research Institute

CCSS is an anisotropic and inhomogeneous material. The manufacturing process can result in the formation of a long columnar (dendritic) grain structure (approximately normal to the surface) with grain growth oriented along the direction of heat dissipation, often several centimeters in length. During the solidification of the material, columnar, equiaxed (randomly speckled microstructure), or a mixed structure can result depending on chemical content, control of the cooling, and other variables in the casting process.

Jeong (1987) described the metallurgical aspects of the grain structure formation as follows: "During the usual solidification process, the transformation of a liquid phase to a solid normally occurs by a process of nucleation and growth. The creation of a solid nuclei and the growth of the solid from these nuclei can proceed at a finite rate only if the system is undercooled below the equilibrium reaction temperature." Further, "Typical alloys always demonstrate melting range between liquidus and the solidus. [Note that the temperature difference between the liquidus and solidus for an 18-8 stainless steel is about 88°C (158°F) according to Figure 1 in Lundin and Chou (1983).] As the alloy cools through the solidification range, solute is rejected at the solid-liquid interface. Since very little mechanical mixing (note, this may not strictly apply to centrifugal casting) of the liquid occurs in the immediate vicinity of the advancing interface, the rejected solute must be redistributed in the liquid by diffusion. The freezing process is so rapid that diffusional processes cannot effectively remove the excess solute near the interface. Hence, solute enrichment occurs at the moving interface until a dynamic equilibrium is reached. The resulting dynamic equilibrium provides an excess of solute in the liquid near the interface with the solute content decreasing to the nominal liquid composition some distance from the interface. As a result, the effective liquidus temperature varies with distance from the interface." Also, "The region within which temperature is less than the effective liquidus temperature is said to experience constitutional supercooling."

Jeong (1987) continues, "The interface (liquid to solid) may vary from being planar, through a cellular, a cellular dendritic, a columnar dendritic, to being equiaxed dendritic mode as the degree of supercooling increases. The extent of constitutional supercooling in a given alloy depends on four factors: (1) the temperature gradient in the liquid, (2) the rate of growth at the solid-liquid interface, (3) the nominal solute content of the alloy, and (4) the diffusion coefficient of the solute in the liquid. (Note that mechanical stirring or vibration, as with rotation, affects diffusion.) Dendritic growth is strongly crystallographic and the primary arms and side branches lie parallel to specified crystallographic directions, e.g., the <100> directions in face centered cubic (FCC) and body centered cubic (BCC) metals and alloys (note, austenite is FCC). These are rapid, easy-growth directions." In general, the solidification mode becomes more dendritic and less desirable, with higher solute contents and austenitic stainless steels have a high solute content, primarily Ni and Cr.

Jackson (1972) offers a more atomistic description of nucleation and crystal structure formation extant during solidification in his report on techniques to control grain structure in austenitic steel castings (CASS). This description may be somewhat too microscopic for the purpose of the present report, but the reference is cited for the reader who may be inclined to further investigate this atomistic metallurgy.

As an introduction for modeling, Temple and Ogilvy (1992) wrote, "Cast stainless steel exhibits at least two identifiably different textures. In one called equiaxed, grains are completely random orientation. It is assumed that, within each grain, the elastic constants are those appropriate to a single crystal of material with a well-defined orientation. The alternate texture has columnar grains which are longer in one direction than the other two, and the crystal axes in the longer direction are correlated between grains." The captions for their Figures 1 and 2 indicate that the macrographs showing the two types of grain structures were from PNNL. "Figure 1: Macrograph of an equiaxed grain structure from a centrifugally cast austenitic pipe, courtesy of Battelle Northwest Laboratory." And "Figure 2: Macrograph of a columnar grain structure from a centrifugally cast austenitic pipe, courtesy of Battelle Northwest Laboratory."

4.2.2 Centrifugal Cast Stainless Steel

According to Northcott and Dicken (1944) and Northcott and Lee (1945), the grain size in centrifugal castings tends to be considerably smaller than that of stationary castings, and that a columnar structure in centrifugal castings shows better mechanical test results than other types of structure. Hall (1948a) contradicts this view. And, Royer (1987) shows two examples of the range of grain structure that can be expected from centrifugal castings, including a uniform columnar (basaltic) from the OD to ID and an eclectic mixture of columnar and equiaxed grains from OD to ID.

The parameters that may affect grain structure include:

- composition
- pouring temperature and speed
- mold material and coating
- mold temperature
- speed of rotation
- vibration
- casting dimensions

<u>Composition</u> – ASM (1992), "The as-cast structures obtained in the horizontal centrifugal casting of steels vary according to composition. Regardless of the phase or phases that solidify first, certain features are common to the structures of centrifugally cast ferrous alloys:

- Very thin, fine columnar skin.
- Well oriented columnar structure adjacent to the skin
- More or less fine equiaxed structure."

However, it is stated that in steels that solidify as austenite, it is relatively easy to obtain well-oriented 100% columnar structures (see #20 Westinghouse Spool Piece, Table 4.4), thus negating the veracity of the previous list of features.

Beeley (1972) writes, "Assuming for example that differential freezing were to produce rejection of a heavier solute element, this would, under perfect directional freezing, segregate to the bore, notwithstanding its greater density. Dispersed crystallization, on the other hand, provides opportunity for gravitational movement of solid and liquid: in the same alloy, therefore, the less dense crystals would be centrifuged towards the bore with the opposite effect to that previously encountered."

Pouring Temperature and Rate – Beeley (1972) under "Structure and Properties," writes "The main quality characteristics of centrifugal cast material is the high standard of soundness arising from the conditions of feeding. This factor is predominant in the improvement of properties relative to those of statically cast material, there being little difference when the latter is perfectly fed. To this advantage may be added a degree of structural refinement, affecting grain size and the distribution of microconstituents." Note, the term feeding is assumed to mean pouring.

According to Cumberland (1963), the ideal solidification behavior is that grain growth commences at the mold wall and proceeds across the section until the last remaining liquid solidifies; giving continuous columnar grains. The Westinghouse Spool Piece, PNNL #B-505, PNNL #B-508, and PNNL #B-515 specimens listed in Table 4.4, show such grain structures. If the pouring rate is so slow that the liquid mass is barely kept ahead of the grains growing from the die wall, then directional solidification will be maintained across the full section and shrinkage cavities will be minimized.

Regarding pouring temperature Beeley (1972) writes, "Low temperature are associated with maximum grain refinement and with equiaxed structures, whilst higher temperatures promote columnar growth in many alloys." And regarding pouring rate, "In practice slow pouring offers a number of advantages: directional solidification and feeding are promoted, whilst the slow development of full centrifugal pressure on the outer solidified skin reduces the risk of tearing" (Beeley 1972). Excessively slow pouring reduces the length of the columnar grains on the OD. Excessively slow pouring in the initial stages leads to surface laps on the OD (e.g., #21 IHI Sw Tech Spool Piece, Table 4.4), which is aggravated by low pouring and mold temperatures. Higher pouring temperatures results in coarser grains but the grain structure from centrifugal casting is not as affected by this parameter as in static casting. Compared to the influence of turbulence, pouring temperature has little effect on grain size in CASS (Northcott and Dickin 1944).

The degree of superheat (pouring temperature) is important when pouring is rapid. High pouring temperatures slows solidification from the OD more than it delays freezing from the bore and (presumably) discourages continuous growth of the OD columnar grains (Northcott and McLean 1945).

Mold Material and Coating – Metal molds provide for more rapid heat extraction and smaller grains than do sand molds and mold coatings are important in modifying the heat transfer rates of some mold materials (ASM 1992). According to Brian Holzaepfel at Sundusky Foundry and Machine Corporation, heat 156529 (see Table 4.4, WOG specimens) was cast in 1978 and the mold had a rammed sand lining 1 to 2 inches thick (see Appendix F email of October 31, 2008). And, according to Gerry Craft (see Section 4.1.2.1, U. S. Pipe Process) U.S. Pipe cast CCSS pipe in heated molds (presumably steel or cast iron molds) sprayed in layers with a diatomaceous silica flour, bentonite, and water slurry, built-up to about 0.1-in. (2.54-mm) thick.

Mold Temperature – ASM (1992) includes, "Numerous investigators have studied the relationship between initial mold temperature and the structure of the resultant casting. Initial mold temperature does not affect the structure of the resultant casting as greatly as the process parameters discussed above do." Regarding mold temperature Beeley (1972) writes, "mold temperature is only of secondary importance in relation to structure."

According to Norcott, higher mold temperatures lead to coarse grains, especially for equiaxed grains; however, the influence of mold temperature on the grain structure was minor compared to some of the other parameters. Nevertheless, a low mold temperature can result in a steep temperature gradient during solidification and this can give rise to banding (Northcott and Dickin 1944).

Rate of Rotation – Regarding rate of rotation, Beeley writes, "Rotational speed also exerts an influence upon structure, the most common effect of increased speed being to promote refinement, although this can also rise from turbulence by instability of the liquid mass at very low speeds. On balance, to secure maximum benefit from centrifugal casting, it is logical to use the highest speed consistent with the avoidance of tearing" (Beeley 1972). A further effect of motion is a tendency for columnar grains to be inclined in the direction of rotation [see Westinghouse Spool Piece in Table 4.4 in this report and Figure 5.2 in Diaz et al. (2007)], evidently due to the movement of under cooled liquid towards the dendrite probes." The inclination of columnar grains is not due to a drag effect because the grains are inclined toward the direction of rotation (Northcott and Dickin 1944).

In general, an increase in rotation speed will reduce grain size, except an excessively slow mold speed tends to produce "tumbling," which leads to turbulence and also promotes small grain size and banding. The IHI SwTech Spool Piece listed in Table 4.4 may be an example of tumbling. Northcott and Dickin (1944) note that this structure has been termed "bacon-streak" in steels (presumably ferritic and martensitic steels). This bacon-streak was also noted in Northcott and McLean (1945).

However, Chopra and Sather (1990) attributed the 100% equiaxed grain structure in two heats of CCSS poured by Sandusky to low pouring temperature or shear between the liquid and solid. The shear would cause dendrites to break and disperse in the liquid-solid boundary. And, in the visit to Manoir Foundry in France, one of the authors, Michael T. Anderson, found that Manoir avoided columnar grain structures by using very high rotation rates (see Table 4.3). Rotational speed is the most important individual parameter influencing the grain structure and segregation. High rotational speed and rapid pouring are the main parameters causing radial cracking (Northcott and McLean 1945).

Vibration – High rotational speed is a major cause of vibration which leads to turbulence in the molten metal. Turbulence has a much greater influence on grain size than does temperature (Northcott and Dickin 1944).

The influence of vibration in producing independently nucleated growth bands under conditions of constitutional supercooling leading to entrapment of solute rich liquid has been cited as contributing to banding (Beeley 1972). Vibration may cause diminution of thermal gradients in the liquid, as well as the possible fragmentation of dendrites to induce the nucleation of bands of equiaxed grains rather than the continuation of dendritic growth (Beeley 1972).

Casting Dimensions – Composition segregation banding occurs only in true centrifugal casting, generally where the casting wall thickness exceeds 50 to 75 mm (2 to 3 in.). Note that all of the specimen thicknesses and wall thickness listed in Table 4.4 were greater than 50 mm (2 in.) except Argonne Pipe P4. Segregation banding rarely occurs in thinner-walled castings (Cumberland 1963; ASM 1992). It is not clear how composition segregation banding differs from the macrostructural banding evident in the CASS pipe and components studied herein; but it would seem that they are interrelated (see Section 4.2.1).

4.2.3 Statically Cast Stainless Steel

Mold Fabrication or Preparation – Sand molds tend to promote slower cooling rates than the permanent metal molds used in horizontal centrifugal casting, thus coarser grain size would likely result. Further, the lack of rotational motion, which tends to refine the grains in centrifugal casting, is absent. Nevertheless, the design of the sprue, gating and riser system, as well as the use of heat sinks, chills, and other techniques can lead to a variety of grain structures and sizes, both columnar and equiaxed, in SCSS components.

Melting and Alloying, Pouring – Alloying considerations are as described for CCSS pipe, and the pouring temperature and rate will affect the grain structure similarly to that of CCSS. Also, the design of the sprue, gating and riser system will affect the cooling, solidification, and grain structure of the SCSS components.

Solidification and Cooling – The cooling process is slower than for CCSS products because the sand mold is not as efficient a heat conductor as the permanent mold material and this generally leads to larger grains and a propensity to columnar grains. However, heat sinks (chills) are often used to enhance thermal conduction.

4.2.4 Banding

A number of types and mixtures of grain structure can be found in both centrifugally cast pipe and statically cast components. This is particularly true for thick-walled castings and often results in bands of various sizes and types of grain structure (see Figure 4.3). Beeley (1972) writes, “Banding, a condition encountered in horizontally cast thick walled cylinders, is a form of structural irregularity in which concentric zones of dissimilar microstructure are associated with segregation of alloy constituents and impurities. Segregation banding occurs only in true centrifugal casting, generally where the casting wall thickness exceeds 50 to 75 mm (2 to 3 in.). It rarely occurs in thinner-wall castings.” Note that all of the specimen thicknesses, wall thickness, listed in Table 4.4, were greater than 50 mm (2 in.) except Argonne Pipe P4. However, banding has also been observed in vibrated, non-rotating molds (Northcott and Dickin 1944). Banding was also evident in some examples of ESCO heat number 28594-3, which was an SCSS casting incorporated in some of the WOG specimens (Table 4.4).

According to Norcott and Dicken (1944), vibration and tumbling are the primary cause of banding (circumferential zones) but a steep temperature gradient, as with rapid pouring or low mold temperature, also contributes to banding.

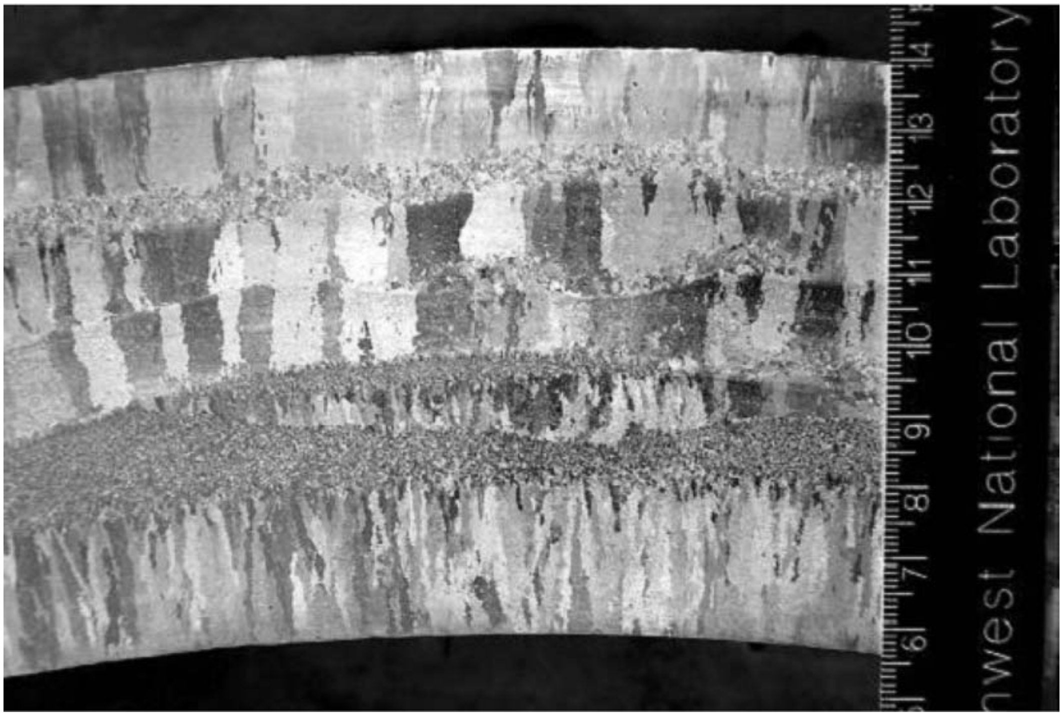


Figure 4.3. Photograph of Polished and Chemically Etched Surface of the IHI Southwest Technologies, Inc., 8.9-cm-Thick Spool Piece Showing Bands of Columnar Grains and Bands of Equiaxed Grains

Beeley (1972) writes, “Alloys undergoing dendritic crystallisation are characterized by regions of columnar and equiaxed growth. The additional factor in the case of centrifugal casting is the relative movement of liquid by slip during acceleration to the speed of the mould. This has been held in some cases to promote columnar growth by disturbance of the growth barrier of solute rich liquid at the interface. The overall effect of motion on structure is, however, complex, since vibration, diminution of thermal gradients in the liquid, and the possible fragmentation of dendrites can also induce the nucleation of equiaxed grains.”

Northcott and Dickin (1944) wrote, “The vibration type of banding is considered to be due to the influence of vibration in limiting the undercooling which a liquid metal normally undergoes before it solidifies. During the normal solidification of an alloy, particularly one having an appreciable freezing range, cooling from the liquid state under conditions giving rise to a steep temperature gradient (as with high pouring rates) brings about a composition gradient in the liquid adjacent to the growing crystals, the plane of the gradient being perpendicular to the mould face. Note that austenitic stainless steel has about an 88 degree C freezing range. The liquid zone in contact with the solid becomes more impure, and therefore of lower freezing point, than the average, so that the liquid next to it away from the mould reaches its freezing point and starts to crystallize.” Thus, a cylinder of solid metal will entrap a cylindrical zone of impure liquid between itself and the growing crystal wall, with the result that the eventual solidification of the impure-liquid zone occurs under conditions of inadequate feeding, so that the segregate zones should be characterized by slight porosity, as they were found to be Northcott and Lee (1945).

Cumberland (1963) offers an alternative explanation for banding in that the bands are incipient laps of fresh molten metal, which if cold and arrive after the previous lap is completely solidified, freezes into a distinct lap (cold shut or lamination). The elaborate banding in IHI SwTech Spool Piece listed in Table 4.4 is likely due to incipient laps. He claims that if the casting conditions are adjusted so that the molten metal distribution is changed to a more uniform flow to eliminate periodic surges, banding will be less likely to occur. Also, he wrote that iron base austenitic steels show the least shrinkage porosity when compared to other ferrous alloys, except cast iron.

Beeley (1972) writes that, “various theories have been advanced as to the cause of banding. These range from the influence of vibration in producing independently nucleated growth bands under conditions of constitutional supercooling leading to entrapment of solute rich liquid, to disturbances created by irregular flow of liquid during formation of the casting: in the later case banding is seen as a result of segregation occurring in the freezing of successively deposited layers of liquid. The condition has been found to occur when some critical level of rotational speed is attained, but has also been associated with very low speeds such as produce sporadic surging of molten metal: both the above mechanisms may therefore be involved.” He continues in the next paragraph, “A further suggested cause of banded structures is freezing metal at the bore and movement of the solidified layer into the casting under centrifugal force due to its higher density: this does not however explain the association of banding mainly with horizontal axis process.”

Thus, there are several conditions, and perhaps mechanisms, that can produce banding in CCSS pipe and vibration, which leads to turbulence, seems to be the most important parameter. However, SCSS castings where no rotation or vibration exists also show banding.

4.2.5 Delta Ferrite

According to the ASM Handbook, page 96, ferrite (delta) content is controlled by composition, and chromium, molybdenum, and silicon promote its formation (ASM 1980).

According to a recent workshop on “Future Directions for the Inspection of CASS,” and based upon studies conducted by Structural Integrity Associates, there may be merit in categorizing CASS pipe and components based upon their delta ferrite content (CGI 2009).

The CF grade cast stainless steel alloys have duplex structures and usually contain 5 to 40% ferrite depending on the particular alloy; these alloys show ferromagnetism. Ferrite is intentionally present in cast CF grade stainless steels for three principal reasons:

- to improve strength,
- to improve weldability, and
- to maximize resistance to corrosion.

Strengthening is provided by the resistance to dislocation movement due to the distribution of ferrite in the primary austenite matrix. In welding, ferrite reduces the propensity of austenitic stainless steels toward hot cracking or microfissuring. And the presence of ferrite in CASS alloys improves the resistance to stress corrosion cracking (SCC) and in general to intergranular attack (ASM 1992).

Note that some of the documents reviewed for this report indicated ferrite content (presumably delta ferrite content) (Chopra and Chung 1985). Also, Westinghouse provided data on 70 heats of cast pipe and 70 heats of cast fittings sampled from LWRs (see Appendix E) and Griesbach et al. (2009), upon reviewing this data, reported that for CF8 the mean delta ferrite number was 20.6 with an upper bound of 25.5; for CF8A, the mean and upper bound were 15 and 16; and for CF8M they were 12.2 and 29.3, respectively. Chopra and Chung (1985) reported both calculated and measured percentages while the Westinghouse data (Appendix E) only reported calculated values via the Schoefer modification of Schaeffler diagram (Aubrey et al. 1982). Measured percentages of 0.9 to 28.4 and calculated percentages of 2.8 to 29.0 were reported by Chopra and Chung (1985), and 12 to 24.5 percent were listed in the Westinghouse report.

Temple and Ogilvy (1992) reported on the modeling of elastic wave propagation through cast austenitic stainless steel. In the introduction under "1.1 Sizewell PWR pump bowl," they provided an example of a casting and described its grain structure as follows: "The pump bowls for the Sizewell B PWR are made from ASME SA351 Grade CF3 stainless steel with the specifications that the castings should contain between 12% and 25% delta ferrite. At the higher ferrite content, a pump bowl casting is likely to consist of an outer layer columnar region and an inner region of equiaxed grains whereas the lower ferrite content is likely to yield a totally columnar grain structure. The grain size increases with a slower rate of cooling. It is the ratio of nickel equivalent to chromium equivalent which controls the grain structure—in the case of low nickel content the delta ferrite precipitates from the molten material and there is a solid state transformation to austenite at a relative low temperature. In the case of higher nickel content, the austenite precipitates at a high temperature and the large columnar grains grow along the direction of the heat flow."

Chopra and Sather (1990) noted that the ferrite content is always lower toward the inner surface of CCSS pipe, apparently related to the nickel content in the material; that is, the concentration of nickel was higher due to the lower solidification temperature .

Aubey et al. (1982) compared several methods of calculating and measuring ferrite in austenitic stainless steels including four computational methods based upon the elemental composition of the steel, two ferromagnetic methods, and a metallographic point-count method. The ferromagnetic methods included the Magne-Gage and the Feritscope. With 50 samples compared, the discrepancy between the point-count, the two measurement methods, and the two best computation methods ranged from zero to eleven percent, with a mean discrepancy of 2.4 percent. According to Ratz and Gunia (1969) the metallographic point-count method gives very consistent results and thus was selected as the standard for Aubrey et al.'s investigation.

Appendix J describes several methods of measuring and calculating ferrite content in austenitic stainless steels, and includes a table showing ferrite percent calculated for selected specimens listed in Table 4.4 using two mathematical models.

Regarding the CCSS ANL specimens listed in Table 4.4 (i.e., P1 to P4), the two with 2.5 to 11.1% ferrite at the OD have columnar grains and the two with 15.9 to 27.6% at the OD have equiaxed grains. Although not statistically significant, this observation supports Temple and Ogilvy's (1992) opinion.

PNNL purchased a Feritscope, which measures ferrite content by magnetic permeability (see Section 4.3.3 and Appendix J). This instrument will be used to make cross-sectional ferrite measurements of CASS specimens that are currently available.

4.2.6 Summary of Grain Structure Development

Austenitic steel castings, whether static or centrifugal, can solidify as columnar, equiaxed, and mixtures of these including banded mixtures (Northcott and Dickin 1944; Jeong 1987; ASM 1992; Temple and Ogilvy 1992).

Centrifugal cast grain structures are affected by many parameters including:

- mold material properties,
- mold coating,
- mold/casting size and shape,
- mold temperature,
- rotation,
- pouring rate and temperature,
- alloy composition,
- etc.;

and, it is possible to get grain structures ranging from the columnar (basalt) to equiaxed, or mixtures of these.

Nevertheless, with a given alloy composition the current literature review indicates that the primary variables controlling CCSS casting grain structure are:

- rate of rotation,
- pouring process,
- pouring temperature, and
- pouring rate.

Of these, rotational rate is the most important parameter affecting grain structure and segregation. Northcott and McLean (1945) attribute this to vibration. However, Chopra and Sather (1990) attributed 100% equiaxed grain structure to low pouring temperatures or liquid/solid shear forces at high rotation speeds; and Manoir Foundry indicated that they avoided columnar grains by using high rotation rates (see Table 4.3). Also, mold wash thickness has been mentioned as having a significant effect on solidification and cooling, and thus grain structure (ASM 1992). According to Brian Holzaephel of SFM (see Appendix F, email of October 31, 2008), the pipe used in the WOG specimens was cast in a mold that had a rammed sand lining 1- to 2-in. thick. Such a lining would slow the thermal conduction and lead to larger grains. Examination of the macrographs available from the literature and listed in Table 4.4, for the WOG specimens with SFM heat number 156529 CCSS pipe shows a number of macrostructures ranging from bands of columnar grains from 1.13- to 2.27-mm wide and 11- to 24-mm long, to bands of equiaxed grains from 1- to 2.42-mm in diameter. Also, a mixture of columnar and equiaxed grains were evident in some bands. The number of band varied from 3 to 4. The wide variety of grain structures shown in the SFM 156529 CCSS pipe heat may also be due to the pouring method.

The grain structure in OPE-2 WOG specimen, which was the only specimen incorporating USP heat number C2291A with macrographs available (Table 4.4), showed 2 or 3 bands with the band nearest the OD composed of columnar grains about 1.13 × 16 mm in size and the other one (or two) bands of equiaxed grains from 2.42 to 1.68 mm in diameter. These sizes are similar to the Sandusky heat even though this pipe was cast into a mold with about a 0.1-mm diatomaceous silica coating, which would have better heat transfer for cooling than the rammed sand mold used by Sandusky. Nevertheless, the pouring methods used by USP may have caused larger grains near the pouring spout (see Section 4.1.2.1, U. S. Pipe Process According to Email of 09/10/08). There is no information available as to where along the length of the pipe, with respect to the pouring spout, that the pipe section for OPE-2 WOG specimen was taken.

High pouring rates and temperatures provide for steep thermal gradients which promote a band of columnar grains at the OD, and low temperatures and low pouring rates provide for smaller columnar grains. Higher pouring temperatures are important when pouring is rapid (Northcott and McLean 1945). The grain structure in OPE-2 WOG specimen (see Table 4.4), which incorporated USP heat number C2291A showed columnar grains on the OD about 1.13 × 16 mm in size. This OD band of columnar grains could have been caused by the high pouring rate and temperature necessitated by the pouring method used; that is, the metal was poured into the mold through a “horn gate” at one end of the mold, not laid like a ribbon as done in the DeLavaud method (see Section 4.1.2.1). Nevertheless, according to Northcott, turbulence has a much greater effect on banding than does temperature and that may have produced the banding seen in OPE-2 WOG. Also, centrifugal pressure may allow for lower pouring temperatures than typical in static casting, and grain refinement is the greatest in true centrifugal casting made in metal dies (Northcott and Dickin 1944). However, perhaps that was not evident in the USP heat because of the pouring technique, nor in the Sandusky heats because of the slow cooling due to the rammed sand lining.

Beeley (1972) writes, “The structures encountered in a large number of individual alloys, particularly the zones (bands) of columnar and equiaxed grains occurring under a wide range of conditions, were described and explained by Northcott and his colleagues (Northcott and Dickin 1944; Northcott and Lee 1945; Northcott and McLean 1945; Lee and Northcott 1947). However, due to the interaction of several mechanisms, it is not at present possible to formulate general rules defining the influence of the main casting variables upon grain structure. In practice, the most consistent influence is that of low pouring temperature in producing grain refinement and equiaxed structures, while somewhat higher temperatures tend to promote columnar grains by suppressing nucleation and increasing radial temperature gradient towards an optimum level.”

Because of the interdependence of the various parameters that affect the grain structure in centrifugal castings, the most reliable methods to optimize them are empirical. Jackson (1972) reported that inoculation was an effective method of reducing grain size in small CASS castings and commented on techniques that might be effective in commercial castings.

According to Northcott and McLean (1945) banding is mainly caused by high rotational rates leading to vibration, which causes turbulence in the molten metal, but the resulting grain structure and size, and the number and size of the bands, are also influenced by pouring temperatures and rates, and banding is also evident in SCSS castings.

The grain structure of static castings is subject to similar influences to those governing the structure of centrifugal castings, the important factors being alloy composition, the temperature gradients and cooling rates induced by the thermal properties of metal and mold, and conditions for independent crystallization. The SCSS elbow, cast by ESCO as heat number 28594-3, showed a variety of grain structures ranging from 1 to 3 bands with columnar grains about 1.13×16 mm in dimension, to mixed grains about 1.15 to 2.47 in dimension, to equiaxed grains 0.76 to 1.67 mm in diameter.

4.3 Types of Grain Structures in CASS Piping

Sections 4.3.1 and 4.3.2 describe the information found in the literature regarding examples of grain structure and banding.

4.3.1 Grain Structures in CCSS Pipe

Anderson et al. (2007) provided examples of grain structures found in several pipe specimens and discussed the structures observed. Fifteen of the specimens were provided by Westinghouse Owners Group. All of the cast WOG pipe samples studied were centrifugally cast and these were welded to statically cast elbows and pump nozzles, as well as wrought safe ends. Other specimens included 12 CCSS pipes with the grain structures described as follows: Two showed bands of course columnar grains mixed with bands of small equiaxed grains and ten showed a mixed matrix of grains. Anderson et al. (2007) remarked that the fabrication parameters that produced the grain structures were unclear.

Diaz et al. (2007) and Anderson et al. (2007) provided the most complete list of cast pipe specimens (mock-ups) to date with both centrifugal and static cast components and pages 5.5 to 5.14 in Diaz et al. (2007) describe the grain structure in the specimens. The specimens from these publications are described in Table 4.4. The average grain size for CCSS pipe was 17 to 20 mm (Diaz et al. 2008).

Table 4.4 provides a collation of information from specimens identified in this project, some of which grain structure information was available.

Following the table is a more detailed description of what each column means.

Table 4.4. Collation of Data and Descriptions of CASS Pipes and Components

Number and Identification	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#1 APE-1 WOG	CCSS (66 wall) pipe-to-SCSS (88.9 wall) elbow: 254 wide, 609.6 long	SFM—156529, CF8A (70/66) ESCO—28594-3 (97/89)	CCSS bands of coarse columnar mixed with bands of small equiaxed SCSS thin-band equiaxed grains	1;14 2;29 3;27 1;42 2;54	MG; 1.52 MG; 1.77 MG; >1.77 MD Col; 1.93x20 MD Equ; 1.67	Diaz et al. (2007) Pg A14 Anderson et al. (2007) Pg 4.15 CCSS GS range = 0.44-8.86 mm Bands 1-3 may be a single. SCSS GS range = 0.89-9.31 mm. Old vintage CCSS (Kim 1988) {Macrograph}
#2 APE-4 WOG	CCSS (66 wall) pipe-to-SCSS (88.9 wall) elbow: 203 wide, 609.6 long	SFM—156529, CF8A ESCO—28594-3	CCSS bands of coarse columnar mixed with bands of small equiaxed SCSS thin-band equiaxed grains			Anderson et al. (2007) Diaz et al. (2007) Old vintage CCSS (Kim 1988)
#3 INE-A-1 WOG	Nozzle (66 wall)-to-safe end (73.7 wall)-to-elbow (63.5): 260 wide, 609.6 long	ESCO—25615-3, CF8A	Nozzle is carbon steel Safe end is forged SCSS elbow is coarse matrix of grains			Anderson et al. (2007) Diaz et al. (2007)
#4 INE-A-4 WOG	Nozzle (66 wall)-to-safe end (73.7 wall)-to-elbow (63.5 wall): 203 wide, 609.6 long	ESCO—25615-3, CF8A	Nozzle is carbon steel Safe end is forged SCSS elbow is coarse matrix of grains			Anderson et al. (2007) Diaz et al. (2007)
#5 INE-A-5 WOG	Nozzle (66 wall)-to-safe end (73.7 wall)-to-elbow (63.5 wall): 254 wide, 609.6 long	ESCO—25615-3, CF8A (70/63.5)	Nozzle is carbon steel Safe end is forged SCSS elbow is coarse matrix of grains	1;66	MD Equ; 1.00	Diaz et al. (2007) Pg A15 Anderson et al. (2007) Pg 4.15 SCSS GS range = 0.38-4.14 mm {Macrograph}
#6 MPE-3 WOG	CCSS pipe (66 wall)-to-SCSS elbow (83.8 wall): 203 wide, 609.6 long	SFM—156529, CF8A ESCO—28594-3	CCSS coarse matrix of grains SCSS coarse matrix of grains			Anderson et al. (2007) Diaz et al. (2007)

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#7 MPE-6 WOG	CCSS pipe (66 wall)-to-SCSS elbow (83.8 wall): 260 wide, 609.6 long	SFM—156529, CF8A (73/66) ESCO—28594-3 (81/84)	CCSS coarse matrix of grains SCSS coarse matrix of grains	1;24 2;25 3;22 1;40 2;23 3;17	WD Col; 2.27×24 WD Equ; 2.20 MD Equ; 3.00 WD Equ; 1.41 MG; 2.47 MG; 1.89	Diaz et al. (2007) Pg A16 Anderson et al. (2007) Pg 4.15 CCSS GS range = 0.56-26.81. CCSS bands 2&3 may be a single. SCSS GS range = 0.28-5.59 mm {Macrograph}
#8 ONP-D-2 WOG	Nozzle (68.6 wall)-to-safe end (73.7 wall)-to-CCSS pipe (63.5 wall): 254 wide, 616 long	UNK,UNK, CF8A SFM—156361,	Nozzle is carbon steel Safe end is forged CCSS pipe is a mixed matrix of course grains			Anderson et al. (2007) Diaz et al. (2007) See Appendix G (Rishel 2008)
#9 ONP-D-5 WOG	Nozzle (68.6 wall)-to-safe end (73.7 wall)-to-CCSS pipe (63.5 wall): 254 wide, 616 long	SFM—156361, CF8A (61/64)	Nozzle is carbon steel Safe end is forged CCSS pipe is a mixed matrix of course grains	1;61	MG; 3.89	Diaz et al. (2007) Pg A17 Anderson et al. (2007) Pg 4.15 CCSS GS range = 0.83-20.27 mm See Appendix G (Rishel 2008) {Macrograph}
#10 ONP-3-5 WOG	Nozzle (66.0 wall)-to-safe end (71.1)-to-CCSS pipe (63.5): 203 wide, 616 long	SFM—156361, CF8A	Nozzle is carbon steel Safe end is forged CCSS pipe is a mixed matrix of course grains			Anderson et al. (2007) Diaz et al. (2007) See Appendix G (Rishel 2008)
#11 ONP-3-8 WOG	Nozzle (66.0 wall)-to-safe end (71.1 wall)-to-CCSS pipe (63.5 wall): 203 wide, 616 long	SFM—156361, CF8A (67/64)	Nozzle is carbon steel Safe end is forged CCSS pipe is a mixed matrix of course grains	1;44 2;23	MG; 3.89 MG; 5.90	Diaz et al. (2007) Pg A18; maybe only one band as ONP-D-5 Anderson et al. (2007) Pg 4.15 CCSS GS range = 0.33-26.67 mm See Appendix G (Rishel 2008) {Macrograph}
#12 OPE-2 WOG	CCSS pipe (58.4 wall)-to-SCSS elbow (71.1 wall): 254 wide, 521 long	USP;C2291A, CF8A or CF8M? (59/60) ESCO—72176-1, CF8M (65/71)	CCSS coarse matrix of mixed grains SCSS coarse matrix of mixed grains	1;30 2;21 1;21 2;40	WD Col; 1.13×30 WD Equ; 2.0 WD Equ; 0.76 PD Col; 1.15×30	Anderson et al. (2007) Diaz et al. (2007) Pg A.19 See Appendix G (Rishel 2008) {1} {Macrograph}

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#13 OPE-5 WOG	CCSS pipe (58.4 wall)-to-SCSS elbow (71.1 wall): 203 wide, 521 long	USP—C2291A, CF8A or CF8M? ESCO—72176-1, CF8M	SCSS coarse matrix of grains CCSS coarse matrix of grains			Diaz et al. (2007) Anderson et al. (2007) Pg 4.15 CCSS GS range = 0.21-16.67, SCSS GS range = 0.21-5.21 mm See Appendix G (Rishel 2008) {1}
#14 POP-7 WOG	SCSS nozzle (83.8 wall)-to-CCSS pipe (66 wall): 254 wide, 533 long	ESCO—24117-2, CF8A SFM—156529	SCSS coarse-mixed matrix of grains CCSS coarse-mixed matrix of grains			Anderson et al. (2007) Diaz et al. (2007)
#15 POP-8 WOG	SCSS nozzle (83.8 wall)-to-CCSS pipe (66 wall): 254 wide, 533 long	ESCO—24117-2, CF8A (69/84) SFM—156529 (63/76)	SCSS coarse-mixed matrix of grains CCSS coarse-mixed matrix of grains	1;69 1;26 2;19 3;27 or 1:77	MD Equ; 1.64 WD Equ; 1.44 MD Equ; 1.89 MD Equ; ?1.89 MO Equ; ~2.0	Anderson et al. (2007) Pg 4.15, SCSS GS range = 0.21-8.26 mm CCSS GS range = 0.21-15.69 Diaz et al. (2007) Pg A.20, CCSS measured next to weld. CCSS is likely OD buttered over a single band of equiaxed grains increasing in size from OD to ID. {Macrograph}
#16 EPRI Spanish Spool Pce Ring	CCSS pipe section: 864 OD, 311 wide, 367 long, 64 wall	UNK;UNK (64/63)	Multibanded and mixed coarse-grained columnar and equiaxed	1;15 2;30 3;20 or 1;15 2;50	WD Col; 1×15 WD Equ; 1.26 WD Equ; 2.89 Bands 2&3 are likely a single; GS ~ 2	Anderson et al. (2007) Pg 4.6, 4.15, 5.5 CCSS GS range = 0.50-7.4 mm, Vintage: mid 1970 to 1980. Also see Diaz et al. (2007) Pg 5.11 & A.10 {Macrograph} {2}
#17 SwRI AAD#1 Spool Piece	Assumed CCSS thick spool piece section: 156 wide, 287 long, 84.1 wall	UNK,UNK (84/84)	Multibanded and mixed coarse-grained columnar and equiaxed			Diaz et al. (2007) Pg 5.11 Macrograph not sufficiently clear to measure band width or GS.

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#18 SwRI AAD#2 Pipe	CCSS pipe section: 130 circumference, 311 wide, 367 long, 71 OD, 65 wall	UNK,UNK (65/65)	Multibanded and mixed coarse grained columnar and equiaxed	1;34 2;13 3;18	WD Col: ~1.5x34 MG; ~2 MD Equ: ~4	Diaz et al. (1998) Pg 3.13,A10 Diaz et al. (2007) Pg 5.11 {Macrgrph}
#19 SwRI AAD#3 Pipe	CCSS pipe section: 127 circumference, 156 wide, 287 long, 91 OD, 84 wall	UNK,UNK (84/33)	Multibanded and mixed coarse grained columnar and equiaxed	Multi-banded		Diaz et al. (1998) Pg3.13, Diaz et al. (2007) Pg5.11 Photomacrograph not sufficiently clear to measure band width or GS.
#20 Westing-house Spool Piece	CCSS spool piece, 130 circumference, 254 long, 710 OD, 64 wall	UNK,UNK (63/64)	CCSS, 1 band, columnar ID to OD; grains oriented along the rotation direction	1;64	WD Col; 3.1×64	Diaz et al. (2007) Pg 5.2, 5.5,5.12,A.11, A.13 Anderson et al. (2007) Pg 4.2, 4.4, 5.4, 4.15 CCSS GS diam. range=0.64-16.32 Vintage: late 1960 to mid 1970 {Macrograph}
#21 IHI SwTech Spool Piece	CCSS spool piece 127 circumference, 152.4 long, 910 OD, 84 wall	UNK; Log 808B Heat C-1207-2 (84/83)	Grain structure varies along the circumference from one band to nine. Two azimuths at one axial position are listed.	1;83 1;16 2;4 3;12 4;3 5;11 6;3 7;6 8;6 9;20	WD Col; ~6×83 WD Col; 5×16 WD Equ; ~1 WD Col; ~8×9 WD Equ; ~1 WD Col; ~5×9 WD Equ; <1 MD Col: ~1.5×4 WD Equ; <1 WD Col; ~2×20	Diaz et al. (2007) Pg 5.1, A.11, A.12 Anderson et al. (2007) Pg 4.1, 5.3, 4.15 GS range <0.2-25 mm. Vintage, early to mid 1960. Heat info. from Lagleder (2008). {Macrograph}

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#22 Westing-house 15 Ring Sgmnts PWS 6.24 Study	CCSS pipe (59 wall)-to-CCSS pipe (59 wall): 812 OD, ~406 axial length	SFM—Ht 155487, CF8A Type 304 SS, (55/59)		1;59	PD Col; ~10×30	Pade and Enrietta (1981) Pg 9-19, A-3 (1 of 8) A.4 Cast before Oct 28, 1976. No chemistry reported.
#23 ANL *** C1 pump casing ring	SCSS Pump Casing (57 wall): OD=600 mm	ESCO—C1, CF-8, (57/57)	Banded, columnar/ equiaxed radial to axial growth near ends	1	MG	Chopra and Sather (1990) Pg 7 Chopra et al. (1991) Pg 4; % ferrite: calc=7.8; meas=2.2 Chopra and Chung (1985) Pg 6 ferrite @ OD=2.3% @ ID=1.7% Chopra (1991) Pg 11 {No Macrograph}
#24 ANL *** P1 pipe	CCSS pipe (63 wall): OD=890 mm	ESCO—P1, CF-8 (63/64)	Equiaxed across thickness	1;63	Equ; ~1–2	Chopra and Sather (1990) Pg 7 Chopra et al. (1991) Pg 4; % ferrite: calc=17.7; meas=24.1 Chopra and Chung (1985) Pg 6 ferrite @ OD=27.6% @ ID=19.5% Chopra (1991) Pg 11 {No Macrograph}

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#25 ANL *** P2 pipe	CCSS pipe (73 wall) OD=930 mm	FAM—P2, CF-3 (73/73)	Equiaxed across thickness	1;73	Equ; ~1–2	Chopra and Sather (1990) Pg 7 Chopra et al. (1991) Pg 4; % ferrite: calc=12.5; meas=15.6 Chopra and Chung (1985) Pg 6 ferrite @ OD=15.9% @ ID=13.2% Chopra (1991) Pg 11 {No Macrograph}
#26 ANL *** P3 pipe	CCSS pipe (73 wall): OD= 580	SFM—P3, CF-3 (76/52)	Banded, radially oriented columnar one equiaxed band (~4 mm deep) at ID		Col; GS not reported Equ; GS not reported	Chopra and Sather (1990) Pg 7 Chopra et al. (1991) Pg 4; % ferrite: calc=2.8; meas=1.9 Chopra and Chung (1985) Pg 6 ferrite @ OD=2.5% @ ID=0.9% Chopra (1991) Pg 11 {No Macrograph}
#27 ANL *** P4 pipe	CCSS pipe (32 wall) OD= 580	SFM—P4, CF-8M (32/34)	Radially oriented columnar		Col; ~1.5×30 to 2.5×30	Chopra and Sather (1990) Pg 7 Chopra et al. (1991) Pg 4; % ferrite: calc=5.9; meas=10.0 Chopra and Chung (1985) Pg 6 ferrite @ OD=11.1% @ ID=9.8% Chopra (1991) Pg 11 {No Macrograph}
#28 CEGB 15 Weld Test Blocks	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A UNK,UNK, CF-8A	Either equiaxed ~2 mm or columnar ~2 mm dia.			(Gilroy et al. 1985) These are PNNL CCSS-RRT specimens

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#29 PNNL #B-504	−CCSS pipe (60 wall)-to-+CCSS pipe (60 wall): 845 OD, 177.8 wide, 404 long	UNK; UNK (58/60) UNK; UNK (58/60)	−CCSS intermediate-size equiaxed +CCSS intermediate-size columnar		Equ; Int Col; Int	Anderson et al. (2007) Pg 4.13 Diaz et al. (2007) Pg 5.9
#30 PNNL #B-505	−CCSS pipe (60 wall)-to-+CCSS pipe (60 wall): 845 OD, 171.5 wide, 400 long	UNK; UNK (58/60) UNK; UNK (58/60)	−CCSS fine grain columnar +CCSS fine grain equiaxed		PD, Col; ~3×16 PD, Equ; ~1-3	Diaz et al. (1998) Pg 3.13, A.2 Diaz et al. (2007) Pg 5.10 Anderson et al. (2007) Pg 4.13 Diaz et al. (1998) disagrees with Diaz et al. (2007) & Anderson et al. (2007) {Macrograph} Note: Diaz et al. (1998) shows coarse grain col on both sides, but describes col and equ on each side. Anderson et al. (2007) describes as fine grain col and equ on each side.
#31 PNNL #B-519	−CCSS pipe (60 wall)-to-+CCSS pipe (60 wall): 845 OD, 181.6 wide, 404 long	UNK; UNK (60/60) UNK; UNK (58/60)	−CCSS intermediate-size columnar +CCSS intermediate-size equiaxed		Equ; Int Col; Int	Anderson et al. (2007) Pg 4.14 Diaz et al. (2007) Pg 5.10
#32 PNNL #B-520	−CCSS pipe (60 wall)-to-+CCSS pipe (60 wall): 845 OD, 175.4 wide, 403.2 long	UNK; UNK (60/60) UNK; UNK (58/60)	−CCSS intermediate-size columnar +CCSS intermediate-size equiaxed		Equ; Int Col; Int	Anderson et al. (2007) Pg 4.14
#33 PNNL CCSS-RRT #1	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (51/60) UNK,UNK, CF-8A (51/60)		1;51 1;51	WD Equ; ~1-3 WD Equ; ~1-3	Bates et al. (1987) Pg C-21 {macrograph}

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#34 PNNL CCSS-RRT #2 & B508	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (51/60) UNK,UNK, CF-8A (54/60)	−CCSS intermediate size equiaxed +CCSS intermediate size columnar	1;51 1;55	WD Equ; ~1-3 WD Col; ~2×55	Bates et al. (1987) Pg C-22 {macrograph} Diaz et al. (1998) Pg 3.13, A.2 Anderson et al. (2007) Pg 4.13
#35 PNNL CCSS-RRT #3 & B528	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (53/60) UNK,UNK, CF-8A (52/60)		1;53 1;52	WD Col; ~2×53 WD Equ; ~2-4	Bates et al. (1987) Pg C-23 {macrograph} Diaz et al. (1998) Pg 3.12
#36 PNNL CCSS-RRT #4	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (54/60) UNK,UNK, CF-8A (50/60)		1;54 1;50	WD Col; ~2×54 Poor image WD Equ;~1-3	Bates et al. (1987) Pg C-24 {macrograph}
#37 PNNL CCSS-RRT #5	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (52/60) UNK,UNK, CF-8A (54/60)		1;52 1;54	WD Equ; ~1-3 WD Col; ~2×54 Poor Image	Bates et al. (1987) Pg C-25 {macrograph}
#38 PNNL CCSS-RRT #6	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (50/60) UNK,UNK, CF-8A (52/60)		1;50 1;52	WD Equ;~1-4 WD Col; ~2×52	Bates et al. (1987) Pg C-26 {macrograph}
#39 PNNL CCSS-RRT #7	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (53/60) UNK,UNK, CF-8A (50/60)		1;53 1;50	WD Col; ~2×53 WD Equ; ~1-3	Bates et al. (1987) Pg C-27 {macrograph}
#40 PNNL CCSS-RRT #8	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (51/60) UNK,UNK, CF-8A (53/60)		1;51 1;53	WD Equ; ~1-3 WD Col; ~2×53	Bates et al. (1987) Pg C-28 {macrograph}

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#41 PNNL CCSS-RRT #9	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (50/60) UNK,UNK, CF-8A (52/60) UNK,UNK, (50/60) CF-8A (50/60) UN(50/		1;50 1;52	WD Equ,~1-3 WD Col; ~2×52 WO Equ;	Bates et al. (1987) Pg C-29 {macrograph}
#42 PNNL CCSS-RRT #10	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (52/60) UNK,UNK, CF-8A (50/60)		1;52 1;50	WD Col; ~3×52 WD Equ; ~2	Bates et al. (1987) Pg C-30 {macrograph}
#43 PNNL CCSS-RRT #11 & B515	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (53/60) UNK,UNK, CF-8A (50/60)	−CCSS intermediate size columnar +CCSS intermediate size equiaxed	1;55 1;50	WD Col; ~2×55 WD Equ;~2	Bates et al. (1987) Pg C-31 {macrograph} Diaz et al. (1998) Pg 3.13 Anderson et al. (2007) Pg 4.14 GS range (Col) 0.6-12 & (Equ) 0.6-7; Pg A.8, Diaz et al. (2007) Pg 5.10
#44 PNNL CCSS-RRT #12	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (51/60) UNK,UNK, CF-8A (53/60)		1;51 1;53	WD Equ; ~1-4 WD Col; ~3×53	Bates et al. (1987) Pg C-32 {macrograph}
#45 PNNL CCSS-RRT #13	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (53/60) UNK,UNK, CF-8A (50/60)		1;53 1;50	WD Col; ~3×53 WD Equ; ~1-3	Bates et al. (1987) Pg C-33 {macrograph}
#46 PNNL CCSS-RRT #14 & B549	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (52/60) UNK,UNK, CF-8A (52/60)	−CCSS equiaxed +CCSS equiaxed	1;52 1;52	WD Equ;~1.5 WD Equ; ~2	Bates et al. (1987) Pg C-34 {macrograph} Diaz et al. (1998) Pg 3.12

Number and Identifi-cation	Configuration and Dimensions (mm)	Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)	Types of Steel in the Components and/or Description of Grain Structure	Band Number and Thickness (mm)*	Grain Type and Average Grain Size (mm)	Remarks and Reference Source
#47 PNNL CCSS-RRT #15 & B501	−CCSS pipe (60 wall)-to- +CCSS pipe (60 wall): 845 OD 400 axial length	UNK,UNK, CF-8A (52/60) UNK,UNK, CF-8A (50/60)	−CCSS intermediate size columnar +CCSS intermediate size equiaxed	1;52 1;50	WD Col; ~2×52 WD Equ;~1-3	Bates et al. (1987) Pg C-35 {macrograph} Anderson et al. (2007) Pg 4.12 Diaz et al. (2007) Pg 5.9
#48 PZR Surge Line	CCSS pipe (31.8 wall) to SCSS elbow: 323.9 OD; 33 wall; 457.2 long	UNK,UNK	CCSS, 2 bands; ID columnar and OD equiaxed SCSS, columnar		CCSS ID band ~1 SCSS 6.35	Diaz et al. (2007, 2008)

Notes:

ANL = Argonne National Laboratory
APE = pipe-to-elbow (auto weld)
CCSS = centrifugally cast stainless steel
CEGB = Central Electricity Generating Board
Cor = coarse grain size; greater than 3 mm
Fin = fine grain size; less than 2 mm
INE = inlet nozzle-to-elbow
Int = intermediate grain size; 2 to 3 mm
MD = moderately defined
MG = mixed grains
MPE = pipe-to-elbow (manual weld)
ONP = outlet nozzle-to-pipe
OPE = outlet pipe-to-elbow
PD = poorly defined
POP = pump outlet-to-pipe
RRT = round robin test
SCSS = statically cast stainless steel
WO = well organized
WOG = Westinghouse Owners Group
WSS = wrought stainless steel

* Bands are numbered from OD to ID
**Measured from figure on the page cited as the source, in mm and classified as columnar, equiaxed, and mixed according to Diaz et al. (1998)
***ANL Argonne National Laboratory

{1} Re. OPE-2, OPE-5: Alloy identification is from RIS08b in Appendix G.
{2} Re. #16 EPRI Spanish Spool Piece Ring: The photomacrograph in Diaz et al. (2007) page 5.11 is very different than the other images of the grain structure of this specimen.

Table 4.4 Explanation

The first column titled "Number and Identification" lists the number used in this report and the identification of the specimens as follows:

- **#1-15** – The first fifteen specimens listed were Westinghouse Owner's Group specimens where APE = Pipe to Elbow (automatic submerged arc welding), INE = Inlet Nozzle to Elbow, MPE = Pipe to Elbow (manual shielded metal arc welding), OPE = Outlet Pipe to Elbow, ONP = Outlet Nozzle to Pipe, and POP = Pump Outlet to Pipe. The CCSS pipe in the APE specimens was old vintage cast pipe manufactured in 1972. The POP specimens were weld overlayed on the OD of the pipe.
- **#16** – The next specimen listed was a large spool piece from the Electric Power Research Institute (EPRI) that had been extracted from a cancelled nuclear power plant in Spain (Anderson et al. 2007; Diaz et al. 2007).
- **#17–19** – The next three specimens listed were from Southwest Research Institute (SwRI), AAD#1 was a thick spool piece, and the other two were thick pipe sections (Diaz et al. 1998; Diaz et al. 2007).
- **#20** – The 20th specimen was a thick spool piece from Westinghouse and was cut from a vintage CSS material (Anderson et al. 2007; Diaz et al. 2007).
- **#21** – The 21st specimen was from IHI Southwest Technologies Inc. and was cut from a vintage CSS material (Anderson et al. 2007; Diaz et al. 2007).
- **#22** – The 22nd was a set of 15 Westinghouse ring weldments fabricated from one ASME SA-351 CF8A, SFM heat number 155487, 32.15-in. (812-mm) OD, 27.5-in. (699-mm) ID, 2.325-in. (59-mm) wall thickness, 22-ft (6.7-m) axial length CCSS pipe, cast in late 1976. The pipe was cut into 30, 8-in. (203-mm) axial length segments, and the segments were circumferentially welded together in pairs to make 15 welded rings (Pade and Enrietta 1981).
- **#23–27** – The next five specimens were listed as ANL specimens and were from one statically cast pump casing ring (C1) and four centrifugal cast pipes (P1 to P4); and included CF-3 and CF-8 grades. The outer diameters of the pipes range from 600 to 900 mm and the wall thicknesses from 38 to 76 mm. The ferrite content was measured using a Feritscope, Auto test FE, Probe Type FSP-1. The ferrite morphology in the various cast materials was globular for ferrite contents of less than 5%, lacey for contents between 5 and 20%, and acicular for larger amounts (Chopra and Chung 1985; Chopra 1991).
- **#28** – The 28th was 15 Central Electricity Generating Board (CEGB) weld test blocks used in the Cast Austenitic Round Robin Exercise (CARRE) and each consisted of an austenitic weld joining two centrifugally cast austenitic pipe sections. The grain structure was either equiaxed or columnar and the pipes were 845-mm OD and 60-mm wall and the welded sections about 200-mm circumferentially by about 400-mm axially (Gilroy et al. 1985).
- **#29–32** – These four specimens were sections cut from butt-welded, 845-mm OD, 60-mm wall CCSS pipe. The pipe material was from two different heats of CCSS ASTM A-351 Grade CF-8A (Diaz et al. 1998; Anderson et al. 2007; Diaz et al. 2007).

- **#33–47** – There were 26 total specimens designated for use in the PNNL CCSS-RRT in the 1980s. All of these specimens were also designated with a B-series identification (numbering) system. Depending on the reference, these specimens may be referred to by using the B-series designation (B-501, B-518, etc.) or by using the blind-testing numbering system used in the international round robin tests (1–15). As determined from the TUBECO documents (see Appendix D) and discussions with PNNL scientists, a portion of a nozzle was fabricated by TUBECO from two centrifugal cast ASTM A351-CF8A stainless steel 27.5-in. (700-mm) ID pipes (heats), 11 feet (33.5 m) and 4.25 feet (13 m) long, respectively. According to Dr. Steven R. Doctor and other knowledgeable PNNL personnel, both of these pipes were cast by Sandusky Foundry and Machine, one with a single band of equiaxed grains OD to ID and the other with a single band of columnar grains. Copies of a number of pages of documents pertaining to the fabrication of a nozzle by TUBECO, Inc. of 123 Varick Ave., Brooklyn, New York 11237, for Westinghouse P. O. 308001 in 1973 were obtained from Dr. Steven Doctor of PNNL Applied Physics and Materials Characterization Sciences Group. Copies of pages pertinent to PNNL specimens discussed in this report are contained in Appendix D.

  One of the 27.5-in. (700-mm) ID pipes used in the TUBECO-fabricated nozzle was centrifugally cast by Sandusky Foundry and Machine Co. as heat number 144179 in about January of 1973, and copies of certifications are included in Appendix D. No information was available as to the grain structure in this heat. The two pipes were circumferentially welded together, and other pieces added to complete the nozzle. Subsequently, as mentioned in Bates et al. (1987), portions of the 700-mm ID section were used to fabricate PNNL specimens with CCSS-RRT designations, five of which were also designated as B-5XX (B-Series). Thirteen of these specimens were circumferential sections of about 25 azimuthal degrees (about 170 to 180-mm chord length, 190-mm circumferential length), and 400-mm in axial length cut from the weldment fabricated from the two 700-mm ID pipes originally part of the Westinghouse nozzle fabricated by TUBECO.

  Apparently, one of the 700-mm pipes used in the TUBECO-fabricated nozzle had a single band of equiaxed grains and the other a single band of columnar grains, which resulted in 13 specimens with different grain structures on each side of the weld. This was discovered after welding of the PNNL CCSS-RRT specimens and when the specimens were sectioned and examined for grain structure. Further, another weldment was also sectioned which had equiaxed grains on both sides of the weld, and which provided CCSS-RRT specimens 1 and 14 reported in Table 2.1, Pg. 2–3 of Bates et al. (1987). Documents did not reveal which of the two grain structures represented the Sandusky heat number 144179. The CCSS-RRT specimens were originally fabricated for use in the PNNL Piping Inspection Round Robin (PIRR) and CCSS round robin tests as part of the Programme for Inspection of Steel Components (PISC) in the early 1980s (Diaz et al. 2007).

  Note that Bates et al. (1987) reported that the PNNL CCSS-RRT specimens were fabricated from 845-mm OD, 60-mm wall thickness CCSS pipes butt-welded together. However, 845-mm OD minus the wall thickness of 60 mm equals 725 mm, which is 25 mm (1-in.) larger than the 700 mm (27.5 in.) specified in the TUBECO Bill of Materials.

- **#48** – The last specimen listed was a pressurizer (PZR) surge line sample, which included an ASME SA 351 G8 CF-8M stainless steel 304.8-mm diameter, Schedule 160 pipe.

The second column titled “Configuration and Dimensions (mm)” describes the configuration of the specimens and provides the dimensions, in mm, with the wall thickness of many specimens shown in parentheses. CCSS = Centrifugal Cast Stainless Steel pipe and SCSS = Static Cast Stainless Steel component.

The third column titled “Foundry, Heat, Alloy and Wall Thickness (Tm/To) (mm)” provides information regarding the foundry that cast the material, the heat number, alloy and wall thickness in mm as-cast (To) and as-measured (Tm) from available macrographs. The foundries are abbreviated as SFM = Sandusky Foundry and Machine, ESCO = ESCO Corporation, USP = U. S. Pipe, FAM = French Foundry, and UNK = Unknown. The heat number of the pipe or component follows and the number is configured according to that of the individual foundry, except when not known (i.e., UNK). The alloy for most specimens is listed according to the ASTM A351 designation as shown under Melting and Alloying in Section 4.1.2 of this report.

The fourth column provides information as to the “Types of Steel in the Components and/or Description of the Grain Structure” in components in the specimen, excluding the weld metal. These descriptions are either as described in the publications referenced in the seventh column or as interpreted by the authors from the referenced macrographs.

The fifth column describes the “Band Number and Thickness (mm)”. The referenced macrographs showed that the macrographs of the pipes and components often showed more than one distinct type of grain structure and these were in bands (see Section 4.2.4, Banding). The band number from 1 to several is shown, as numbered from the OD to the ID, followed by the thickness of the band in mm after the semicolon.

The “Grain Type and Average Grain Size” in mm is listed in the sixth column. The grain type as interpreted by the authors from the referenced macrographs include PD = Poorly Defined, WD = Well Defined, MG = Mixed Grain (i.e., columnar and equiaxed), MD = Moderately Defined, Col = Columnar and Equ = Equiaxed. The grain type is followed by the estimated average grain size in mm. Only one diameter is provided for the equiaxed and mixed, and a diameter and length is provided for the columnar. Some of the references provided a qualitative value for the grain size [e.g., Int = Intermediate, judging from the grain sizes reported for other specimens in Diaz et al. (2007), Intermediate grain size is probably 2 to 3 mm in diameter].

The last column, entitled “Remarks and Reference Source,” provides remarks and lists the source of the data as referenced in the References section of this report. Also, the note {Macrograph} is used to indicate that a macrograph showing the grain structure is available in at least one of the references given.

Table 4.5 lists three WOG specimens from SFM heat number 156529 for which photomacrographs were available (#1, #7, and #15). This is a single heat (pipe) but the grain structures shown in Dias et al. (2007), pages A-14, A-16, and A-18 are markedly different. APE-1 shows three bands of equiaxed grains ranging from 1.53 to greater than 1.77-mm diameter, MPE-6 shows three bands with columnar grains about 2.27 × 24 mm at the OD followed by two bands of equiaxed grains ranging from 2.2 to 3.0 mm at the ID. Finally, ONP-3-8 shows two bands of much larger equiaxed grains, about 3.9-mm diameter at the OD and 5.9-mm at the ID. These photomacrographs indicate that a single heat poured by Sandusky with a 1- to 2-in. rammed sand lining produced a variety of bands and macrostructures.

The WOG specimens ONP-D-5 (#9) and ONP-3-8 (#11) listed in Table 4.4 includes sections from SFM heat number 156361 pipe and although the latter seems to have two bands, it is very similar in appearance to ONP-D-5. Both specimens have large equiaxed grains ranging from about 3.9 to 5.9 mm in diameter from OD to ID.

Table 4.5. Available Macrographs of Westinghouse CCSS Specimens Including Foundry and Heat Number

Westinghouse ID	Foundry	Heat No.	Reference
APE-1	SFM	156529	Diaz et al. (2007)
MPE-6	SFM	156529	Diaz et al. (2007)
ONP-D-5	SFM	156361	Diaz et al. (2007)
ONP-3-8	SFM	156361	Diaz et al. (2007)
OPE-2	USP	C22914	Diaz et al. (2007)
POP-8	SFM	156529	Diaz et al. (2007)
15 Ring Segment	SFM	155487	Pade (1981)

The WOG specimen OPE-2 (#12 listed in Table 4.4) incorporates a section of pipe from USP heat number C22914 and shows a macrostructure very similar to that of MPE-6 (#7) cast by Sandusky. They both show columnar grains at the OD, with the grains in the SFM pipe being larger, and the one or two bands of equiaxed grains following in USP are similar at the ID to those in SFM heat. The larger grains in the SFM pipe might be explained by the rammed sand liner of the mold, which would reduce the efficiency of heat transfer.

Also, Pade and Enrietto (1981) studied 15 ring weldments (#22 listed in Table 4.4) fabricated from thirty 8-in. (20.3-cm) long segments cut from one pipe 32.15-in. (81.5-cm) OD by 27.5-in. ID (70.0-cm) and 22-ft (6.7-meters) long CF8A CCSS. The pipe was radiographed and ultrasonically examined before cutting at Sandusky, so it seems a reasonable assumption that it was cast by SFM and the heat number was 155487 as shown on the Westinghouse Radiographic Inspection Report Number 21527, dated 10/28/76, on page A-5 of Pade and Enrietto. Some photomacrographs of the weld area on page 9-19 of Pade and Enrietto (1981) show two bands each about 29-mm wide; with columnar grains at the OD, about 7-mm wide by 28-mm long, and equiaxed grains at the ID ranging from 5 to 15-mm diameter. These are significantly larger than the grains shown in the other SFM heats (castings). Other photomacrographs were shown, but they were not sufficiently clear to reveal the grain structure.

Table 4.6 lists specimens from Chopra and Chung (1985) (#23–#27) who wrote “The commercial heats included sections of four centrifugal cast pipe and a static-cast pump impeller and a pump casing ring. The outer diameter and wall thickness of the cast pipes raged from 0.6 to 0.9 m and 38.1 to 76.2 mm, respectively.” And “Two castings, P1 and P2, contained equiaxed grains across the entire thickness of the pipe. The grain size and distribution were not significantly different in the three orientations (axial, circumferential, and redial planes). The other two centrifugal cast pipes, P3 and P4, showed radially oriented columnar grains. Pipe section P3 also contained a band of small equiaxed grains near the ID. This band was relatively thin, i.e., ~4 mm deep, and probably formed accidently. The columnar grain castings are expected to have uniform properties in the axial and circumferential directions.” Chopra and Sather (1990) also reported on these specimens and showed photomacrographs.

Table 4.6. Pipe and Ring Castings Described in Chopra and Chung (1985)

Identi-fication	Configurations w (Wall Thickness) & Dimensions in cm	Grain Structure	Ferrite Content OD/ID	Grain Size SCSS in mm[a]	Remarks
C1	SCSS (5.71) Pump casing ring, 60 OD	SCSS Banded, columnar/ equiaxed radial to axial growth near ends	2.3/1.7	Not Reported	Grade CF-8
P1	CCSS (6.35) Pipe, 89 OD	Equiaxed across thickness	27.6/19.5	1–2	Grade CF-8
P3	CCSS (5.16) Pipe, 58 OD	Banded, radially oriented columnar and equiaxed band (~ 4 mm deep) near ID	2.5/0.9	Not Reported	Grade CF-3
P2	CCSS (7.3) Pipe, 93 OD	Equiaxed across thickness	15.9/13.2	1–2	Grade CF-3
P4	CCSS (3.18) Pipe, 58 OD	Radially oriented columnar	11.1/9.8	1.5×30 to 2.5×30	Grade CF-8M

(a) Grain size estimated from photomacrographs in Chopra and Sather (1990).

WESDYNE (A Westinghouse NDE Company) performed a random sampling survey of 70 heats of cast pipe and 70 heats of cast fittings, and the spread sheets showing the chemistry and mechanical properties are included in Appendix E. These samplings were from 15 Westinghouse Nuclear Power Plants constructed between 1969 and 1976. Both ASTM A351 CF8M (equivalent to 316 wrought stainless steel composition) and CF8A (equivalent to 304L wrought stainless steel composition) alloys are reported. The cast fittings consisted of 60 heats of CF8M and 10 heats of CF8A. Delta ferrite content is shown, as estimated from a Schaeffler diagram or reported in the certifications, for some of the samples in the Appendix E spreadsheets. The CCSS pipe listed in Appendix E were cast by U. S. Pipe or Sandusky.

Behravesh (1986) published copies of macrographs showing two types of grain structure in CCSS pipe labeled as (a) Mixed-Type Grains (PNL) and (b) Mixed-Type Grains (Vogtle Power Plant).

Anderson et al. (2007) also studied specimens described as PNNL specimens (see Table 4.4, #29 to #47) consisting of sections cut from butt-welded, 845-mm (933.3-in.) OD, 60-mm (2.4-in.) wall CCSS pipe. The CCSS pipe material was from two different heats of ASTM A-351 Grade C-8A (Diaz et al. 1998). They described the grain structure in these CCSS pipe as “intermediate-size columnar grains” on six of the pipe, “fine grained equiaxed grain” on one, “intermediate-size equiaxed grain” on six, and “fine grained-columnar grains” on one. Anderson et al. (2007) presented macrographs showing the grain structure of many of the CCSS pipe mock-ups and specimens reported; e.g., on pages 4.3, 4.4, 4.6, 5.3, 5.4, and 5.5 in that report.

Taylor (1984) compared a Westinghouse study with a PNNL study of CCSS pipe. On page 1, Taylor writes, “1.1 AN OVERVIEW OF THE INSPECTION PROBLEM. Processes for manufacturing centrifugally cast stainless steel (CCSS) pipe in the U. S. before 1976 resulted in a long, columnar grain structure with grain growth oriented along the direction of heat dissipation. Grains formed from this process attained several centimeters in length (see Westinghouse Spool Piece in Table 4.4). After 1976, the process control was improved and a more equiaxed grain structure, similar to that found in an isostatic casting, was achieved. The two different grain structures have significantly different UT properties.”

Gilroy et al. (1985) on page 1 (see Table 4.4, #28) wrote, "2. TEST BLOCK DESCRIPTION. The test blocks used in the Cast Austenite Round Robin Exercise (CARRE) each consisted of an austenitic weld joining two centrifugally cast austenitic pipe sections. The grain structure of the parent materials was either equiaxed or columnar [Plate (1)] and the pipes themselves were ~845 mm diameter with a wall thickness ~60 mm. Each welded section was approximately ~200 mm circumferentially (an approximately 30 degree section of 845 OD pipe) by ~400 mm axially." Note that their Plate (1) figure showed macrographs of columnar and equiaxed grain structures. They listed 10 blocks (specimens) using numbers from 1 to 14; excluding 4, 5, 8, and 9. No details were provided as to the dimensions or grain structure of individual blocks.

Bates et al. (1987) on page 2-1 (see Table 4.4, #33 to #47) provided a description of the pipe specimens they studied. "PHYSICAL DESCRIPTION. The CCSS specimens used in the screening phase of the CCSS RRT consist of sections cut from butt-welded, 845-mm OD, 60-mm thick centrifugally cast stainless steel pipe. The CCSS pipe material was from two different heats of ASTM A-351 Grade-8A." These may be the same specimens as the "blocks" in Gilroy et al. (1985). They provided a table (Table 2.1) entitled "Characteristics of CCSSRRT (Centrifugal Cast Stainless Steel Round-Robin Test) Screening Phase Specimens." Note that their Appendix C contains macrographs of the grain structure of each section. Macrographs on pages C-21 to C-36 show a variety of grain structures, also D-18, D-23, D-27, D-30, D-39, and D-43 to D-48.

Anderson et al (2007) and Diaz et al. (2007) provided examples of grain structures found in several specimens and discussed the structure observed. The specimens are listed in Table 4.4 of this report and include #1 through #21, #29 through #32, #34, #35, #43, and #46 through #48.

4.3.2 Grain Structures in SCSS Pipe

The grain structure of the statically cast WOG components listed in Table 4.4 (#1, #5, #7, #12 through #15) were from four heats (castings) cast by ESCO (28594-3, 25615-3, 72176-1, and 24117-2). Heat number 28594-3 showed 2 to 3 bands with both columnar and equiaxed grains at the OD and equiaxed and mixed for the other bands. Heat number 25615-3 had only one photomacrograph, which showed one band of equiaxed. Heat number 72176-1 had only one photomacrograph, which showed two bands, the OD being equiaxed and the ID columnar. Heat number 24117-2 had only one photomacrograph, which showed a single band of equiaxed grains. The equiaxed grains ranged from less than 1 mm to 3 mm and the columnar from about 2×20 to 1×30 for these four ESCO heats.

The static-cast pump casting ring (Table 4.4, #23) shown in Chopra and Chung (1985) showed a mixed structure of columnar and equiaxed grains. A change from radial to axial growth of the columnar grains was observed. The grain structure observed in the SCSS pipe is likely typical of large thick-walled CASS castings.

4.3.3 Delta Ferrite and Grain Structure

Temple and Ogilvy (1992) noted that the grain structure in SCSS pump bowl castings at higher ferrite content tended toward an outer layer of columnar grains and an inner layer of equiaxed grains whereas the lower ferrite content was likely to yield totally columnar grains. It is the ratio of nickel equivalent to chromium equivalent which controls the grain structure–in the case of low nickel content the delta ferrite precipitates from the molten material and there is a solid-state transformation to austenite at a relative low temperature. In the case of higher nickel content, the austenite precipitates at a high temperature and the large columnar grains grow along the direction of the heat flow. This implies that high delta ferrite content may be an indicator of the propensity to develop equiaxed grains, and conversely low delta ferrite may indicate columnar grains. To test this hypothesis, PNNL has purchased a Feritscope and will survey available specimens of known grain structure for ferrite content.

5.0 Discussion of Results

Note: When paragraphs in this section are prefaced with numbers in parentheses, such as (6.1), they are indicating a correlation with the numbered paragraphs in Section 6.0, Conclusions.

5.1 Grain Structure in Specimens

Table 5.1 condenses the information shown in Table 4.4, collating heat numbers and macrographs from which grain type and size information could be obtained. The first five rows list centrifugal (CCSS) pipe castings produced by Sandusky (SMF) and U. S. Pipe (USP). The next 18 rows list pipe casting from unknown (UNK) sources. The last five rows list static (SCSS) castings all produced by ESCO. The first column lists the foundry that cast the pipe or component and the casting process. The next column lists the heat and the shape (pipe, elbow, etc.). The third column lists the specimen identification, the fourth the number of bands, the fifth the grain structure in each band, the sixth the grain size in each band, and the last column pertinent remarks.

Table 5.1. Summary List of CASS Pipe and Component Heats and Grain Structures with Macrographs Available

Foundry/ Cast Type	Heat No./ Shape	Specimen	No. Bands	Band No.[a] & Grain Type	Band No. & Grain Size, mm	Remarks
SMF/ Centrifugal	156529/ Pipe	APE-1 WOG	3	1-Columnar 2-Mixed 3-Mixed	1-1.52 2-1.77 3->1.77	Bands 1, 2, & 3 may be 1 band
SMF/ Centrifugal	156529/ Pipe	MPE-6 WOG	3	1-Columnar 2-Equiaxed 3-Equiaxed	1-2.27×24 2-2.20 3-3.00	Bands 2 and 3 may be 1 band
SMF/ Centrifugal	156529/ Pipe	POP-8 WOG	3	1-Equiaxed	1-~2	
SMF/ Centrifugal	155487/ Pipe	Westinghouse 15 Ring Segment	2	1-Columnar 2-Equiaxed	1-~10×30	
SMF/ Centrifugal	144179 / Pipe	PNNL-CCSS RRT #1 to 15	1	1-Columnar or 1-Equiaxed	1 ~ 2×53 or 1 ~ 2	Heat #144179 is either equiaxed or columnar grain structure
USP/ Centrifugal	C2291A/ Pipe	OPE-2 WOG	3	1-Columnar 2-Equiaxed	1-1.13×30 2-2	
UNK Centrifugal	UNK/ Pipe	ONP-D-5 WOG	1	1-Mixed	1-3.89	Columnar & equiaxed
UNK/ Centrifugal	UNK/ Pipe	ONP-3-8 WOG	2	1-Mixed 2-Mixed	1-3.89 2-5.90	Columnar & equiaxed; bands 1 & 2 may be 1 band
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-505 +Side	1	1-Equiaxed (see note)	1-~3×16	Note: Diaz et al. (1998), Fig. A.1 shows a coarse grain columnar on + side of weld

Foundry/ Cast Type	Heat No./ Shape	Specimen	No. Bands	Band No.[a] & Grain Type	Band No. & Grain Size, mm	Remarks
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-505 −Side	1	1-Columnar (see note)	1-~5×16	Note: Diaz et al. (1998), Fig. A.1 shows a coarse grain columnar on −side of weld
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-508 +Side	1	1-Columnar	1-~2×55	
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-508 −Side	1	1-Equiaxed	1-~2	
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-515 +Side	1	1-Equiaxed	1-~2	
UNK/ Centrifugal	UNK/ Pipe	PNNL #B-515 -Side	1	1-Columnar	1-~2×55	
UNK/ Centrifugal	UNK/ Pipe	EPRI Spanish Spool Piece Ring	1 or 2	1-Equiaxed 1-Columnar 2-Equiaxed	1-~3 1-1×15 2-~2	Note: Diaz et al. (2007), Figs. 5.4 & A.31 show 2 different structures; Anderson et al. (2007), Figs. 4.6 and 5.8.
UNK/ Centrifugal	UNK/ Pipe	SwRI AAD#2	2	1-Columnar 2-Mixed 3-Equiaxed	1-~1.5×34 2-~2 3-~4	
UNK/ Centrifugal	UNK/ Pipe	Westinghouse Spool Piece	1	1-Columnar	1-~3×64	Anderson et al. (2007), Fig. 5.6, pg. 5.4 shows 180° segment
UNK/ Centrifugal	Log 808B Heat C-1207-2/ Pipe	IHI SwTech Spool Piece	2 to >8	1-Columnar 2-Columnar and 1-Columnar 2-Equiaxed 3-Columnar 4-Equiaxed 5-Columnar 6-Equiaxed 7-Columnar 8-Equiaxed 9-Columnar	1-~6×83 and 1-~5×16 2-~1 3-~8×9 4-~1 5-~5×9 6-~<1 7-~1.5×4 8-~<1 9-~2×20	Note: Diaz et al. (2007), Fig. A.28, pg. A.11 shows both the 2- and 9-banded structures; and Fig. 5.1, pg. 5.1 shows the complexity of grain structure in the 9-banded structure.
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #10 +side	1	1-Equixed	1-~2	
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #10 −Side	1	1-Columnar	1-~3×52	
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #11 +Side	1	1-Equiaxed	1-~2	
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #11 −Side	1	1-Columnar	1-~2×55	
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #14 +Side	1	1-Equiaxed	1-~1.5	
UNK/ Centrifugal	UNK/ Pipe	PNNL CCSS-RRT #14 −Side	1	1-Equiaxed	1-~2	

Foundry/ Cast Type	Heat No./ Shape	Specimen	No. Bands	Band No.[(a)] & Grain Type	Band No. & Grain Size, mm	Remarks
ESCO/ Static	28594-3/ Elbow	APE-1 WOG	2	1-Columnar 2-Equiaxed	1-1.93×20 2-1.67	
	28594-3/ Elbow	MPE-6 WOG	3	1-Equiaxed 2-Mixed 3-Mixed	1-1.41 2-2.47 3-1.89	Bands 2 and 3 may be 1 band
ESCO/ Static	25615-3/ Elbow	INE-A-5 WOG	1	1-Equiaxed	1-1.00	
ESCO/ Static	72176-1/ Elbow	OPE-2 WOG	2	1-Equiaxed 2-Columnar	1-0.76 2-1.15×30	
ESCO/ Static	24117-2/ Nozzle	POP-8 WOG	1	1-Equiaxed	1-1.64	

(a) Bands numbered from OD to ID.

5.2 Centrifugal Cast Stainless Steel (CCSS)

(6.1) The five specimens, including three heats listed in the first five rows of Table 5.1, indicate that significantly different grain structures may result from presumably the same casting process parameters at a given foundry. The grain structures in these three heats cast by Sandusky ranged from single bands of either 100 percent columnar or 100 percent equiaxed, to up to three bands of columnar, equiaxed, or mixed grains. Columnar grains at the OD would indicate strong directional cooling with a solidification rate slow enough to allow replenishment of the higher temperature solidifying solute at the advancing columnar dendrites, or sufficient mixing of newly added molten metal with the remaining liquidus phase through liquid/solid shear or vibration. This scenario would also apply to the one heat that showed 100 percent columnar grains from OD to ID. The specimen that showed 100% equiaxed grains from OD to ID may have been the result of higher rotation rates, as used by Manior, or a unique set of casting parameters including composition, pouring rate, pouring temperature, and rate of rotation. Nevertheless, these five specimens, all cast by a single foundry, indicate that an individual foundry using presumably consistent practices, can produce a wide variety of grain structures.

Some of the macrographs from specimens listed in Table 5.1 could be identified with coming from a single heat (pipe). These include those macrographs from IHI SwTech Spool Piece and several of the Westinghouse Owners Group (WOG) specimens incorporating SFM heat number 156529. The section of the IHI specimen shown in Figure A.29 of Diaz et al. (2007) is a slice of a CASS pipe at one axial position. The macrostructure shown varies along the circumference from a single band of columnar grains from OD to ID, to various combinations of bands, up to eight, and grain types and sizes. This IHI example illustrates the eclectic variety of grain structure that can result in a single pipe due to the interaction of parameters and mechanisms extant in centrifugal casting of austenitic steel pipe. Another, less eclectic sampling, identified as being from a single heat, can be illustrated by comparing the macrostructures from SFM heat number 156529 incorporated in WOG specimen APE-1, MPE-6, ONP-5, and POP-8 listed in Table 5.1. APE-1 and MPE-6 show three bands, including a band of columnar grains at the OD and two bands of mixed, or equiaxed, at the center and ID. ONP-D-5 shows a single band of mixed grains from OD to ID, and POP-8 shows a single band of equiaxed. All four of these show different grain structures even though three are from the same heat and all are from the same foundry.

This difference in grain structure for the SFM pipe may be due to pouring from one end only and/or the rammed sand mold lining. Information from none of the specimens indicate where along the length of the pipe the sampled macrostructure was taken; for example, center, end, etc. These examples illustrate that the grain structure in a single heat of CCSS pipe may vary in terms of grain type, grain size, and number of bands.

(6.2, 6.3) The main parameters controlling grain structure in CCSS pipe of a specific composition are rate of rotation, pouring temperature, and pouring rate (Northcott and Dickin 1944; Northcott and McLean 1945; Beeley 1972; ASM 1992). According to Beeley (1972) low pouring temperatures are associated with refined equiaxed grains while higher temperatures promote columnar grains. And slow pouring promotes directional solidification but shorter columnar grains at the OD (Northcott and McLean 1945).

The variability in the grain structures of the Sandusky (SFM) heats associated with the five specimens listed in Table 5.1, and which were poured into steel or iron molds lined with a rammed sand lining 1- to 2-inches thick (see email of October 31, 2008, Appendix F) supports the views stated in the literature that other parameters are more important than the type or temperature of the mold (Northcott and Dickin 1944; Northcott and McLean 1945; Cumberland 1963; Beeley 1972; ASM 1992). Moreover, OPE-2 incorporates a section of pipe from U. S. Pipe heat number C22914 and shows a macrostructure very similar to the CCSS pipe of MPE-6 cast by Sandusky even though U. S. Pipe used a mold wash that was only about 0.1-inches thick compared to the 1- to 2-inch-thick rammed sand of Sandusky. Also, recent correspondence from USP (see Appendix F email of September 18, 2008) indicated that heat number C2291A likely was cast by pouring the molten metal through a “horn gate” such that the metal had to run down the whole length of the mold instead of being laid in a ribbon as with the DeLavaud method (ASM 1992). The “horn gate” pouring method likely resulted in different grain structures and banding at the opposite ends of the pipe. The end where pouring was initiated would experience higher temperatures in order to assure that the metal would remain molten and flow to the opposite end of the mold. Whereas, at the opposite end the metal, would have cooled to some degree. Thus, the macrographs from OPE-2 WOG specimen may have been the result of the hot end of the mold where the metal was poured, and thus had large grains as discussed in Section 4.2.2 under <u>Pouring Temperature and Rate</u> and by Northcott and Dickin (1944). Conversely, two CCSS heats, SFM 156529 (MPE-6) and USP C2291A (OPE2), Table 5.1 and Table 4.4, showed the same number of bands, and similar grain structure, even though they were cast with different molds and pouring conditions (see emails in Appendix F).

Thus, due to the interaction of several parameters and mechanisms effecting grain structure in CCSS pipe, it is not possible to formulate general rules defining their specific influence (Beeley 1972). And, according to Hall (1948b), in practice, pouring rate, pouring temperature, and rotation speed for CCSS are empirically determined. Nevertheless, rate of rotation affects turbulence and has the most effect on grain structure; and to secure the maximum benefit, it is logical to use the highest speed consistent with avoidance of tearing. Also vibration due to high rotation rates is likely to induce nucleation of equiaxed grains (Beeley 1972).

(6.4, 6.5, 6.6, 6.7, 6.8 Bands) Banding is common in CCSS (Northcott and Dickin 1944; Cumberland 1963; Beeley 1972; Anderson et al. 2007; Diaz et al. 2007). According to Northcott and Dickin (1944), banding in CCSS pipe is primarily induced by vibration due to high rotation rates, and the character of the grain structure within the band is affected by pouring rate and temperature. Nevertheless, banding is common in CASS and is found in static casings as well (Northcott and Dickin 1944; Northcott and McLean 1945). Other parameters affecting banding in CCSS castings include pouring temperature, pouring rate, mold material, and casting thickness (Northcott and Dickin 1944; Northcott and McLean 1945; Beeley 1972).

Papers written in the 1960s and 1970s indicate that banding was common in CASS pipe, “Most alloys are susceptible to banding, but the wider the solidification range and the greater the solidification shrinkage the more pronounced the effects may be” (Cumberland 1963; Beeley 1972). Note that the temperature difference between the liquidus and solidus for an 18-8 (austenitic) stainless steel is about 88°C (158°F) according to Figure 1 in Lundin and Chou (1983), while that for AISI 1008 (carbon) steel is about 30°C (54°F). The coefficient of thermal expansion is ~18 µ-meter/°C (~10 µ-inch/°F) for AISI 304 compared to ~14 µ-meter/°C (~8 µ-inch/°F) for AISI 1008 steel. Thus, the shrinkage for austenitic stainless steel is about 20% greater than for carbon steel and this directly affects the rate of cooling because of the casting shrinking away from the mold. The combination of a wide solidification range and large shrinkage makes austenitic stainless steel much more prone to banding than most other steels, and considering the procedures that the foundries contacted in the investigation exercised to minimize vibration, it is likely that factors other than vibration caused banding in most of the specimens listed in Table 4.4 and Table 5.1.

According to the literature, thick-walled CASS castings can exhibit a variety of grain structures including columnar, equiaxed, and mixtures of these (Northcott and Dickin 1944; Beeley 1972; Jeong 1987; ASM 1992; Temple and Ogilvy 1992) in bands of varying grain types and sizes. This was confirmed by the macrographs listed in Table 5.1 and Table 4.4. Of the five examples of Sandusky (SMF) centrifugal cast pipe shown in Table 5.1, two show columnar grains on the OD and two mixed or equiaxed grains. Nine of the 24 specimens listed in Table 5.1 show banded structures.

(6.9, 6.10, 6.11, 6.12 Grain Structure) In the CCSS specimen grain structures listed in Table 5.1, columnar grains were found in 13 of the 24 CCSS specimens listed. Columnar grains were found about half the time at the OD. Chopra and Sather (1990) noted that ferrite content is always lower toward the ID of CCSS pipe, apparently related to the nickel content; that is, enrichment of nickel in the liquidus near the ID. And this higher nickel content would promote columnar grains. And further, according to the literature, high solute content, as with austenitic stainless steels, and thick sections lead to a tendency toward large columnar grains (Cumberland 1963; Jeong 1987). Also, these columnar grains will be aligned, approximately, with their <100> crystallographic direction parallel to the radial direction of the pipe.

The grain structures observed in the examples described in Section 4.3 and listed in Table 5.1 confirm the findings in Section 4.2; that is, that the number and variability of process parameters can produce an eclectic variety of grain structures, including banding in CCSS pipe. The grain sizes for the three SMF heats listed are on the order of 1–2 by 50 mm for the columnar grains and about 2 mm for the equiaxed. The fourth SMF specimen listed, from heat number 155487, showed somewhat larger grains.

The last CCSS pipe listed in Table 5.1 with its foundry and heat identified in WOG specimen OPE-2 was cast by U. S. Pipe (USP) and it shows columnar grains on the OD. Its bands and grain sizes are similar to the SFM pipe heat number 156529 in WOG MPE-6.

The remaining CCSS pipe listed in Table 5.1 are of unknown (UNK) heats and unknown (UNK) foundries. Five of the eighteen specimens show banded structures and eight of the eighteen showed columnar grains. The columnar grain sizes ranged from 1.5 to 8-mm wide and from 4 to 63-mm long. Where a single band of columnar grains was shown (PNNL #B-505, PNNL #B-508, PNNL #B-515, Westinghouse Spool Piece, PNNL CCSS-RRT #10, and PNNL CCSS-RRT #11), many of the grains extended from OD to ID of the pipe wall.

The number of bands of equiaxed grains ranged from a single band in PNNL #B-505, PNNL #B-508, PNNL #B-515, EPRI Spanish Spool Piece, PNNL CCSS RRT#11, and PNNL CCSS RRT#14, to nine bands of columnar and equiaxed through the wall in IHI SwTech Spool Piece.

The grain structures illustrated in the photomacrographs available from the CCSS specimens listed in Table 5.1 showed that the CCSS pipe castings had both uniform grain type from OD to ID in a single band, and banding. The CCSS pipe showed columnar, equiaxed, and mixed types of grains in both the single and multiple bands. The equiaxed grain sizes ranged from 1 to nearly 6 mm in diameter, the mixed grains from less than 2 to nearly 6 mm in dimension, and the columnar from about 1.5 to 8-mm wide and 4 to 63-mm long.

Comparison of the grain sizes in CCSS with those in SCSS castings indicate that the equiaxed grains in CCSS averaged 1.7 times larger, the mixed 1.4 times larger, and the columnar 2 times in width and 1.5 larger in length (see Table 5.1 and Table 4.4). Thus, the CCSS grains tended to be larger than the SCSS grains, which contradicts the literature (Northcott and Dickin 1944; Northcott and Lee 1945). This may have been due to the casting processes used or that the preferred alloy, with the ESCO castings, was SA351-CF8M (see Table 4.4 WOG specimens).

5.3 Statically Cast Stainless Steel (SCSS)

(6.16, 6.17 Casting Parameters) The SCSS components listed in Table 5.1 include four elbows and one nozzle from four different heat numbers. APE-1 and MPE-6 are the same heat but show different grain structures through the wall thickness. It is not known whether both structures are from the same or different areas in the same casting or from two castings. The main parameters controlling grain structure with a given alloy in SCSS are design of the mold, mold material, mold/casting size and shape, pouring temperature, and pouring rate (ASM 1992; De Garmo et al. 1997; Groover 2004). The grain structures observed in the examples described in Section 4.3 and listed in Table 4.4 confirm the findings in Section 4.2; that is, that the number and variability of process parameters can produce an eclectic variety of grain structures, including banding in SCSS piping components.

(6.18, 6.19, 6.20, 6.21 Banding) Banding is common in SCSS pipe components of the type investigated in this report (Northcott and Dickin 1944; Cumberland 1963; Beeley 1972; Anderson et al. 2007; Diaz et al. 2007) and is affected by the parameters mentioned previously. Examples of macrostructure from SCSS pipe components listed in Table 5.1 showed that the number of bands ranged from one equiaxed band in INE-A-5 and POP-8 to two bands, the OD columnar and the ID equiaxed in APE-1 and the OD equiaxed and the ID columnar in OPE-2. Further MPE-6 showed three bands, the OD equiaxed and the next two mixed. The grain size for the columnar averages about 1.5×25 mm, and the equiaxed between about 1 and 2 mm. Discussion previously made in this section regarding CCSS pipe and the broad solidification range of cast austenitic stainless steel and the propensity towards banding also applies to SCSS.

(6.22, 6.23 Grain Type) According to the literature, thick-walled CASS castings can exhibit a variety of grain structures including columnar, equiaxed, and mixtures of these (Northcott and Dickin 1944; Beeley 1972; Jeong 1987; ASM 1992; Temple and Ogilvy 1992) in bands of varying grain types and sizes. Nevertheless, according to the literature, the high solute content in SCSS and thick sections lead toward a tendency to produce large columnar grains (Cumberland 1963; Jeong 1987). This was confirmed in that half the SCSS castings listed in Table 5.1 showed columnar grains. Further, the SCSS castings showed equiaxed grain sizes from less than 0.8 to nearly 1.7-mm diameter, mixed grains from about 1.9 to nearly 2.5 mm in dimension, and columnar grains from about 1.2 to 2-mm wide and 20 to 30-mm long.

The grain structures observed in the examples described in Section 4.3 and listed in Table 4.4 confirm the findings in Section 4.2; that is, that the number and variability of process parameters can produce an eclectic variety of grain structures, including banding in CCSS and SCSS piping components.

5.4 Cast Austenitic Stainless Steel (CASS)

(6.25, 6.25 General) Of the 29 specimens listed in Table 5.1 the foundry source and heat number of only 10 could be identified. Thus, the limited information correlating grain structure, foundry, and heat number compromised the firmness with which conclusions could be drawn.

The CF grade cast stainless steel alloys (CASS) have duplex structures usually containing 5 to 40 percent ferrite depending on the particular alloy (ASM 1992). Temple and Ogilvy (1992) opined that the grain structure in CASS with lower ferrite content is likely to tend toward columnar grains.

A combination of inoculation and high ferrite content may provide conditions that will produce consistently fine equiaxed grains in CASS and these conditions plus high rotation speeds may produce fine equiaxed grains OD to ID in CCSS pipe (Jackson 1972; Temple and Ogilvy 1992, and Table 4.3 CCSS at Manior).

6.0 Conclusions

6.1 The grain structures in CCSS pipe cast by an individual foundry can vary significantly in terms of grain type, grain size, and number of bands and also significant variation can be found within a single heat.

6.2 Theory and experience indicate that the main parameters controlling the production of a single band of equiaxed grains in CCSS thick-walled pipe are:

- rate of rotation,
- pouring process,
- pouring temperature, and
- pouring rate,

and the maximum benefit is obtained with high rotation speeds.

6.3 Experience shows that due to the interaction of several mechanisms, it is not possible to formulate general rules defining the influence of the main casting variables upon grain structure in CCSS.

6.4 Theory and experience indicate that banding is common in CCSS pipe.

6.5 Banding in thick-section CCSS piping is common due to the wide temperature range between the liquidus and solidus and the large shrinkage occurring upon solidification and cooling.

6.6 Banding in CCSS pipe can be produced by any one, or combination, of casting parameters.

6.7 Banding in CCSS pipe is aggravated by vibration, and the character of the bands (number, width, and grain structure) is also affected by the pouring rate and temperature.

6.8 Theory and experience indicate that columnar, equiaxed, and mixed grain structure is common in CCSS pipe and these may occur in bands through the wall thickness.

6.9 The high solute content of thick-walled CCSS castings make them prone to the development of columnar grains.

6.10 Grain structure examples in CCSS pipe found in the literature ranged from a single band of columnar or equiaxed grains, from OD to ID, to nine bands of both columnar and equiaxed grains from OD to ID.

6.11 The grain structures found in the available macrographs in the literature illustrate the following:

a. CCSS pipe castings showed both uniform grain type from OD to ID, and banding.

b. CCSS castings showed columnar, equiaxed and mixed grain type.

c. CCSS castings showed equiaxed grain sizes from less than 1 to nearly 6 mm in diameter and columnar from 1.5- to 8-mm wide and 4- to 63-mm long.

6.13 Grain structure examples representing current CCSS pipe casting processes were not available.

6.14 Except for information regarding the CCSS pipe casting processes at Manoir, current casting processes for CCSS pipe could not be obtained.

6.15 The grain structure in a single heat of SCSS components cast by an individual foundry may vary in terms of grain type, grain size, and number of bands.

6.16 Theory and experience indicate that the main parameters controlling SCSS grain structure with a specific alloy in thick-walled pipe components are:

- design of the mold (chills, sprue, gating and riser system),
- mold material,
- mold/casting size and shape,
- pouring temperature, and
- pouring rate.

6.17 Theory and experience indicate that banding is common in SCSS castings.

6.18 Banding in thick-section SCSS components is common due to the wide temperature range between the liquidus and solidus and the large shrinkage occurring upon solidification and cooling.

6.19 Banding in SCSS components can be produced by any one, or combination, of several casting parameters.

6.20 Theory and experience indicate that columnar, equiaxed, and mixed grain structures are common in SCSS castings, and these may occur in bands through the wall thickness of the component.

6.21 Grain structure examples of SCSS components found in the literature ranged from a single band of equiaxed grains from OD to ID to three bands of both columnar and equiaxed grains from OD to ID.

6.22 The high solute content of thick-walled SCSS castings make them prone to the development of columnar grains.

6.23 The grain structures found in the available macrographs illustrate the following:

a. SCSS castings showed both uniform grain type from OD to ID, and banding.

b. SCSS castings showed columnar, equiaxed, and mixed-grain type.

c. SCSS castings showed equiaxed grain sizes from less than 1 to nearly 2 mm in diameter and columnar from about 1- to 2-mm wide to 20- to 30-mm long.

6.24 The very limited amount of information on CASS relating the foundry and heat number to specific grain structure, particularly photomacrographs, diluted the firmness of the conclusions that could be drawn.

6.25 The propensity for the development of columnar grains in CASS pipe and components may be enhanced by low ferrite content of the casting alloy.

6.26 Equiaxed grains of fine grain size may result in CASS from compositions that tend to produce high ferrite content and inoculation techniques; and for CCSS, a combination of high ferrite, inoculation, and high rotation speeds may produce consistently fine equiaxed gains.

7.0 Recommendations

7.1 It would be beneficial to determine the foundry and foundry-production parameters of more of the specimens identified in this report. This would shed light on how the existing microstructures in these specimens were generated. In addition, correlating this information with existing knowledge of microstructures (orientation, size, morphology, etc.), along with potential data from delta ferrite measurements, would help develop a better understanding of the existing variability in microstructures; possibly providing insights into specific process parameters and their impact on microstructure. Acquiring fabrication data and correlating these data to existing microstructures are first-steps in developing a reliable process for effective determination, or prediction, of existing microstructures in operating plants. Merging these data with in-situ methods to characterize or classify these microstructures should allow NDE inspectors to optimize inspection parameters and more effectively tailor their NDE procedures on CASS components; in turn, enhancing detection and sizing capabilities in these challenging materials.

7.2 It would be beneficial to examine and document the grain structures for all of the available specimens identified in this report. This would include polishing and etching of appropriate surfaces and analyzing grain types and sizes. By piecing together fabrication history and key process parameters used for the various specimens available to PNNL in this study, it may be possible to begin to determine which fabrication parameters play the most important roles in microstructure development and to understand attempts to control variability in those specific parameters. Visually quantifying the microstructures for those sample specimens that are available is important for establishing microstructural measurements (average diameter, orientation, spatial variability, etc.) and correlating existing data with fabrication history. As more of the information is made available, these types of correlations can be made, and the ability to better determine/predict the existing microstructures will be enhanced. This information is also critical toward building a foundation for improved CASS microstructural fabrication processes for next-generation piping.

7.3 It would be beneficial to measure the ferrite content and range from many of the specimen heats identified in this report using the magnetic permeability method (e.g., Feritscope). The ferrite content and range could also be calculated from composition, where available. This information could prove to be crucial in determining grain size in-situ, if the delta ferrite content can be reliably assessed by an electromagnetic method in the field. Presently, the NRC and IRSN are working together to determine if a method can be found to determine grain size. A variety of technical approaches are being assessed to determine the viability for in-situ microstructural characterization/classification. By obtaining additional data through the acquisition of delta ferrite measurements, our ability to correlate ferrite content with microstructure should help to increase measurement confidence. By fusing acoustic measurements and electromagnetic measurements, multiple microstructural signatures (or fingerprints) can be obtained, essentially helping to build the foundation for an effective and reliable in-situ measurement procedure to be developed for determination of grain size, orientation, and morphology, prior to a NDE examination. Knowing grain size theoretically means that NDE parameters such as frequency and inspection angles can be tuned to enable more effective examinations.

8.0 References

AFS. 1957. *Cast Metals Handbook*. American Foundrymen's Society (AFS), Des Plaines, Illinois.

Anderson MT, SL Crawford, SE Cumblidge, KM Denslow, AA Diaz and SR Doctor. 2007. *Assessment of Crack Detection in Heavy-Walled Cast Stainless Steel Piping Welds Using Advanced Low-Frequency Ultrasonic Methods*. NUREG/CR-6933, PNNL-16292, U.S. Nuclear Regulatory Commission, Washington, D.C.

ASM. 1979. *Source Book on Stainless Steels*. American Society for Metals, Metals Park, Ohio, Materials Park, Ohio.

ASM. 1980. *ASM Handbook, Volume 3, Alloy Phase Diagrams*. ASM International, Materials Park, Ohio.

ASM. 1992. *ASM Handbook, Volume 15: Casting*. ASM International, Materials Park, Ohio.

Aubrey LS, PF Wieser, WJ Pollard and EA Schoefer. 1982. "Ferrite Measurement and Control in Cast Duplex Stainless Steels." In *Stainless Steel Castings, ASTM STP 756*, eds: VG Behal and AS Melilli. American Society for Testing Materials, West Conshohocken, Pennsylvania.

Bates DJ, SR Doctor, PG Heasler and E Burck. 1987. *Stainless Steel Round Robin Test: Centrifugally Cast Stainless Steel Screening Phase*. NUREG/CR-4970, PNL-6266, PISC III Report No. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

Beeley PR. 1972. *Foundry Technology*. Halsted Press Division, Wiley & Sons, New York.

Behravesh MM. 1986. "Ultrasonic Inspection of Welded Joints in Centrifugally Cast Stainless Steel Pipes of PWR's Main Coolant Loops." Presented to ACRS Metal Components Subcommittee, June 25, 1986, Pittsburgh, Pennsylvania.

CGI. 2009. "Future Directions for the Inspection of CASS." In *Summary Report: 2nd International Workshop on the Future Directions for the Inspection of Cast Austenitic Stainless Steel Piping*. June 15–16, 2009, Seattle, Washington. Chockie Group International (CGI).

Chopra OK. 1991. *Estimation of Fracture Toughness of Cast Stainless Steel During Thermal Aging in LWR Systems*. NUREG/CR-4513, ANL-90/42, R2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and HM Chung. 1985. *Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems - Annual Report October 1983 - September 1984*. NUREG/CR-4204, ANL-85-20, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and A Sather. 1990. *Initial Assessment of the Mechanisms and Significance of Low-Temperature Embrittlement of Cast Stainless Steels in LWR Systems*. NUREG/CR-5385, ANL-89/17, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK, A Sather and LY Bush. 1991. *Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems, April-Sept. 1989*. NUREG/CR-4744, Vol 4, No. 2, ANL-90/42, U.S. Nuclear Regulatory Commission, Washington, D.C.

Cumberland J. 1963. "Centrifugal Casting Techniques." *The British Foundryman* January:26-47.

Davis GJ. 1973. *Solidification and Casting*. Wiley, New York. ISBN 0470198710 9780470198711.

De Garmo EP, JT Black and RA Kohser. 1997. *Materials and Processes in Manufacturing, 8th ed.*, Prentice Hall, Upper Saddle River, New Jersey. ISBN 0-02-328621-0.

DeGarmo EP, JT Black and RA Kohser. 1997. *Materials and Processes in Manufacturing*. Prentice Hall, Upper Saddle River, New Jersey.

Diaz AA, AD Cinson, SL Crawford, SE Cumblidge, KM Denslow, M Morra, MS Prowant and MT Anderson. 2008. *Technical Letter Report: Assessment of Ultrasonic Phased Array Testing for Cast Austenitic Stainless Steel Pressurizer Surge Line Piping Welds and Thick Section Primary System Cast Piping Welds*. PNNL-17698, Pacific Northwest National Laboratory, Richland, Washington.

Diaz AA, SR Doctor, BP Hildebrand, FA Simonen, GJ Schuster, ES Andersen, GP McDonald and RD Hasse. 1998. *Evaluation of Ultrasonic Inspection Techniques for Coarse-Grained Materials*. NUREG/CR-6594, PNNL-11171, U.S. Nuclear Regulatory Commission, Washington, D.C.

Diaz AA, RA Mathews, J Hixon and SR Doctor. 2007. *Assessment of Eddy Current Testing for the Detection of Cracks in Cast Stainless Steel Reactor Piping Components*. NUREG/CR-6929, PNNL-16253, U.S. Nuclear Regulatory Commission, Washington, D.C.

Flinn RA. 1963. *Fundamentals of Metal Casting*. Addison-Wesley, Reading, Massachusetts. TS230.F53.

Gilroy KS, J Duffy, BA McGrath, DJ Hanstock and AM Stansfield. 1985. *Ultrasonic Inspection of Welds in Centrifugally Cast Austenitic Pipe - CEGB Results in an International Round Robin Exercise, May 1985*. NWR/SSD/85/0098/M, PWR/RCC/MWG/P(85)/545.

Griesbach TJ, G Cofie and RO McGill. 2007. "An Update on Flaw Tolerance Evaluation Studies on Thermally Aged Cast Austenitic Stainless Steel Piping." In *6th International Conference on NDE in Structural Integrity for Nuclear and Pressurized Components*. October 8–10, 2007, Budapest, Hungary.

Griesbach TJ, V Marthandan and H Qian. 2009. *Flaw Tolerance Evaluation of Thermally Aged Cast Austenitic Stainless Steel Piping*. EPRI Report No. 0800209.401, Revision 0, Project 0800209.00, File No. 0800209.00, Electric Power Research Institute, Palo Alto, California.

Groover MP. 2004. *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems*. Wiley & Sons, Hoboken, New Jersey.

Hall JH. 1948a. "Centrifugal Casting of Steel." *The Foundry* 76(8):77pf.

Hall JH. 1948b. "Centrifugal Casting of Steel (Part II)." *The Foundry* 76(9):74pf.

Hall JH. 1948c. "Centrifugal Casting of Steel (Part III)." *The Foundry* 76(10):77pf.

Jackson WJ. 1972. "Control of the Grain Structure in Austenitic Steel Castings." *Iron and Steel* 45(2):163-172.

Jeong YH. 1987. *An Ultrasonic Material State Classifier for Elastically Anisotropic Materials, Vol. 1, Appendix B, Metallurgical Aspects of the Grain Structure Formation*. Ph.D. Thesis, Drexel University, Philadelphia, Pennsylvania.

Kim CC. 1988. *Fabrication of Test Samples for Ultrasonic Evaluation*. WCAP-11998, Westinghouse Electric Corp., Pittsburgh, Pennsylvania. Westinghouse Class 3 WOG Designated Distribution.

Lagleder G. 2008. Email of August 12, 2008, to Michael T. Anderson from Glagleder@ihiswt.com.

Lee ORJ and L Northcott. 1947. "The Centrifugal Casting of Copper Alloy Wheels in Sand Molds." *The Journal of the Institute of Metals* LXXIII:491–520.

Lundin CD and CPD Chou. 1983. *Hot Cracking Susceptibility of Austenitic Stainless Steel Weld Metals*. WRC Bulletin 289, Welding Research Council, New York.

Massoud J-P, C Boveyron, P Ould, G Bezdikian and H Chuier-Bessenec. 1998. "Effect of the Manufacture Process on Thermal Ageing of PWR Duplex Stainless Steel Components." In *6th International Conference on Nuclear Energy (ICONE)*. May 10–14, 1998, San Diego, California. American Society of Mechanical Engineers (ASME), New York. Paper 6085.

Northcott L and V Dickin. 1944. "The Influence of Centrifugal Casting (Horizontal Axis) Upon the Structure and Properties of Metals." *The Journal of the Institute of Metals* LXX:301–323.

Northcott L and ORJ Lee. 1945. "The Centrifugal Casting of Aluminum Alloy Wheels in Sand Molds." *The Journal of the Institute of Metals* LXXI:93–130.

Northcott L and D McLean. 1945. "The Influence of Centrifugal Casting Upon the Structure and Properties of Steel." *The Journal of the Iron and Steel Institute* CLI:303-328.

NUREGs. *Nuclear Regulatory Commission Reports Prepared by NRC Contractors*. Nuclear Regulatory Commission, Washington, D.C. Available at www.nrc.gov/reading-rm/doc-collections/nuregs/contract/.

Pade ER and JF Enrietta. 1981. *Reliability of Ultrasonic Test Method for Detecting Natural Fatigue Cracks in Centrifugally Cast Stainless Steel Pipe*. WCAP-9894, Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

Ratz GA and RB Gunia. 1969. "How Accurate are Methods for Measuring Ferrite?" *Metal Progress* 95(1):76–80.

Rishel RD. 2008. "Cast Stainless Steel Pipe." Email from RD Rishel to CO Ruud, June 27, 2008.

Royer A. 1987. "The Horizontal Centrifugation: A Technique of Foundry Well Adapted to the Processing of High Reliability Pieces." In *ASM Proceedings of an International Conference on Advanced Casting Technology*. November 12–14, 1986, Kalamazoo, Michigan. ASM International, Metals Park, Ohio.

Taylor TT. 1984. *An Evaluation of Manual Ultrasonic Inspection of Cast Stainless Steel Piping*. NUREG/CR-3753, PNL-5070, U.S. Nuclear Regulatory Commission, Washington, D.C.

Temple JAG and JA Ogilvy. 1992. *Propagation of Ultrasonic Elastic Waves in Centrifugally Cast Austenitic Steel*. AEA-RS-4223, AEA Reactor Services.

Woo HH, RW Mensing and BJ Benda. 1984. *Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR Plant, Volume 2: Pipe Failure Induced by Crack Growth, Load Combination Program*. NUREG/CR-3660, Vol. 2; UCID-19988, Vol. 2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Appendix A

Literature Search

Appendix A

Literature Search

Note that references cited are listed in Section 8.0, References, in order of the first author and year.

Alers GA. 1991. *Application of Electromagnetic Acoustic Transducers to Coarse-Grained Material*. NP-7438, Electric Power Research Institute, Palo Alto, California. Final Report, Research Project 2687-5.

Alexandreanu B, Y Chen, OK Chopra, HM Chung, EE Gruber, WJ Shack and WK Soppet. 2007. *Environmentally Assisted Cracking in Light Water Reactors: Annual Report, January – December 2005*. NUREG/CR-4667, ANL-06/33, Volume 36, U.S. Nuclear Regulatory Commission, Washington, D.C.

Ammirato F, P Jeong, S Lucas, A Scott and B Sanders. 1989. "NDE of Cast Stainless Steel in Nuclear Plants." *Nuclear News* March:59–62.

ASM. 1948. *Metals Handbook*. American Society for Metals (ASM), Cleveland, Ohio. pps. 1260 and 1261, Cr-Fe-Ni phase diagrams.

ASM. 1976. *The Metallurgical evolution of Stainless Steels: A Discriminative Selection of Outstanding Articles and Papers from the Scientific Literature*. American Society for Metals, Metals Park, Ohio.

Bates DJ, SH Bush and SR Doctor. "Status Report on Stainless Steel Round Robin Test Cast Stainless Steel Screening Phase." Prepared for PISC III Managing Group.

Beller LS. 1986. *A New View of the Ultrasonic Behavior of Cast Austenitic Steels*. EGG-M-09787, EG&G Idaho, Inc., Idaho Falls, Idaho.

Bencharit U, JL Kaufman, NM Bilgutay and J Saniie. 1986. "Frequency and Spatial Compounding Techniques for Improved Ultrasonic Imaging." In *IEEE 1986 Ultrasonics Symposium*, pp. 1021–1026. November 17–19, 1986, Williamsburg, Virginia. IEEE, New York.

Bilgutay NM and J Saniie. 1984. "The Effect of Grain Size and Flaw Visibility Enhancement Using Split-Spectrum Processing." *Materials Evaluation* 42(6):808–814.

Chopra OK. 1999. *Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels*. NUREG/CR-5704, ANL-98/31, U.S. Nuclear Regulatory Commission, Washington, D.C.

Collected copies of papers entitled "EPRI CCSS Workshop II" (in box provided by A. Diaz)

Doctor SR. Notes from EPRI CCSS Workshop II (in box provided by A. Diaz)

Gavenda DJ, PR Luebbers and OK Chopra. 1997. *Effects of LWR Coolant Environments on Fatigue Design Curves of Austenitic Stainless Steels*. NUREG/CR-5704, U.S. Nuclear Regulatory Commission, Washington, D.C. Available at http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr5704/cr5704.pdf (March 2007).

Chopra OK. 2002. *Mechanism and Estimation of Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments*. NUREG/CR-6787, U.S. Nuclear Regulatory Commission, Washington, D.C. Available at http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6787/cr6787.pdf (March 2007).

Chopra OK, B Alexandreanu and WJ Shack. 2005. *Effect of Material Heat Treatment on Fatigue Crack Initiation in Austenitic Stainless Steels in LWR Environments*. NUREG/CR-6878, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK, EE Gruber and WJ Shack. 2003. *Fracture Toughness and Crack Growth Rates of Irradiated Austenitic Stainless Steels*. NUREG/CR-6826, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK, A Sather and LY Bush. 1991. *Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems, April–Sept. 1989*. NUREG/CR-4744, Vol 4, No. 2, ANL-90/42, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and WJ Shack. 1995. *Mechanical Properties of Thermally Aged Cast Stainless Steels from Shippingport Reactor Components*. NUREG/CR-6275, ANL-94/37, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and WJ Shack. 2001. *Environmental Effects on Fatigue Crack Initiation in Piping and Pressure Vessel Steels*. NUREG/CR-6717, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chung HM and WJ Shack. 2006. *Irradiation-Assisted Stress Corrosion Cracking Behavior of Austenitic Stainless Steels Applicable to LWR Core Internals*. NUREG/CR-6892, U.S. Nuclear Regulatory Commission, Washington, D.C.

Curtis III AE. No date. "Westinghouse Owners Group-Demonstration of Flaw Detection and Characterization Capabilities for Ultrasonic Inspection of Main Coolant Loop Welds."

Diaz AA, RV Harris Jr. and SR Doctor. 2008. *Field Evaluation of Low-Frequency SAFT-UT on Cast Stainless Steel and Dissimilar Metal Weld Components*. NUREG/CR-6984, PNNL-14374, U.S. Nuclear Regulatory Commission, Washington, D.C.

Ericsson L. Oktober 1994. *Reduction of Material Noise in Ultrasonic Nondestructive Evaluation Using Synthetic Frequency Diversity Algorythms*. UPTEC 94 108R, Teknikum Institute of Technology, Uppsala University, Uppsala, Sweden. ISSN 0346-8887.

Eriksson B, T Stepinski and B Vagnhammar. 1996. *Ultrasonic Characterization of Defects, Part 3. Experimental Verification*. SKI Report 96:75, Swedish Nuclear Power Inspectorate, Stockholm, Sweden. ISSN 1104-1374, ISRN SKI-R-96/75BSE.

Fredriksson H and U Akerlind. 2006. *Materials Processing during Casting*. John Wiley & Sons, Chichester, England. ISBN 0470015144 9780470015131, TS 230.F74.

Gianuzzi AJ. 1986. *LWR Experience with Centrifugally Cast Stainless Steel Pipe*. EPRI NP-4996-LD, RP-2405-11, Electric Power Research Institute, Palo Alto, California.

Gavenda DJ, WF Michaud, TM Galvin, WF Burke and OK Chopra. 1996. *Effects of Thermal Aging on Fracture Toughness and Charpy-Impact Strength of Stainless Steel Pipe Welds*. NUREG/CR-6428, U.S. Nuclear Regulatory Commission, Washington, D.C.

Gruber GJ and H Kapitza. December 1980. *Detection of Surface Cracks in Bimetallic Coarse-Grained Structures – A Reliability Evaluation of Six Ultrasonic Techniques*. IzfP, Saarbrucken, Germany.

Hall JH. December 1948. "Patterns and Molding Methods for Steel (Part II)." *The Foundry* 76(12):92pf.

Hall JH. February 1949. "Patterns and Molding Methods for Steel (Part IV)." *The Foundry* 77(2):90pf.

Hall JH. January 1949. "Patterns and Molding Methods for Steel (Part III)." *The Foundry* 77(1):76pf.

Hall JH. March 1949. "Patterns and Molding Methods for Steel (Part V)." *The Foundry* 77(3):92pf.

Hall JH. November 1948. "Patterns and Molding Methods for Steel." *The Foundry* 76(11):80pf.

Hannah KJ and WL Glynn. 1970. *Ultrasonic Test Procedures for Inspection of Centrifugally Cast Stainless Steel Pipe*. TR 70-70. Prepared for Westinghouse by Automation Industries Evaluation Group, November 1, 1970.

Hargreaves ML. 1988. *Digital Processing of Ultrasound Signals Back-scattered from Coarse Grained Austenitic Stainless Steel*. Ph.D. Thesis, University of Keele, Keele, Staffordshire, England.

Heine RW, CR Loper and PC Rosenthal. 1967. *Principles of Metal Casting*. McGraw-Hill, New York, TS 230.H4.

Holman GS and CK Chou. 1985. *Probability of Pipe Failure in the Reactor Coolant Loops of Westinghouse PWR Plant, Volume 1: Summary Report*. NUREG/CR 3660, Vol. 1, UCID-19988, Vol. 1, U.S. Nuclear Regulatory Commission, Washington, D.C.

Jansson C. 1990. "Degradation of Cast Stainless Steel Elbows After 15 Years in Service." In *Fontevraud II International Symposium*. September 10–14, 1990, Royal Abbey of Fontevraund-France.

Jayet-Gendrot S, P Gilles and C Migne. 1997. "Behavior of Duplex Stainless Steel Casting Defects under Mechanical Loadings." In *Proceedings of the 1997 ASME Pressure Vessels and Piping Conference*, pp. 107–116. July 27–31, 1997, Orlando, Florida. American Society of Mechanical Engineers, New York.

Jeong P. 1986. *Metallurgical Aspects of the Grain Structure Formation, Appendix B*. EPRI RP-1570-2, Electric Power Research Institute, Palo Alto, California.

Jeong P. 1985. "Current Status and Design Considerations of an Automated Ultrasonic Pipe Inspection System." Prepared for the 11th World Conference on Nondestructive Testing, Las Vegas, November 3–8, 1985.

Kupperman DS, KJ Reimann and J Abrego-Lopez. 1987. "Ultrasonic NDE of Cast Stainless Steel." *NDT International* 20(3):143–206.

Lundin CD and CPD Chou. 1983. *Hot Cracking Susceptibility of Austenitic Stainless Steel Weld Metals*. WRC Bulletin 289, Welding Research Council, New York.

Lundin CD, W Ruprecht and G Zhou. 1999. *Literature Review: Ferrite Measurement in Austenitic and Duplex Stainless Steel Castings*. Materials Joining Group, Department of Materials Science and Engineering, The University of Tennessee, Knoxville, Tennessee. Submitted to SFSA/CMC/DOE. Available at http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=9DB11EA11118511B2526F3BB32F6CFD2?purl=/14580-mGkMzM/webviewable/.

Michaud WF, PT Toben, WK Soppet and OK Chopra. 1994. *Tensile-Property Characterization of Thermally Aged Cast Stainless Steels*. NUREG/CR-6142, ANL-93/35, U.S. Nuclear Regulatory Commission, Washington, D.C.

Ngoc T. 1987. "Sizing of Y-Shaped Cracks with Ray-Tracing Interpretation"

NRC. 1978. *Control of Ferrite Content in Stainless Steel Weld Metal, Rev. 3*. Regulatory Guide 1.31, U.S. Nuclear Regulatory Commission, Washington, D.C.

Rishel RD. 1987. "Ultrasonic Inspection of Cast Stainless Steel Materials." Presented at the EPRI Seminar on "Cast Stainless Steel Inspection," January 8 and 9, 1987.

Rishel RD. June 27, 2008. "Cast Stainless Steel Pipe," email from RD Rishel to CO Ruud.

Romanoff P. 1981. *The Complete Handbook of Centrifugal Casting*, Tab Books, Blue Ridge Summit, Pennsylvania.

Rose JL, A Tverdokhlebov, A Pilarski, K Balasubramaniam and D Diprimeo. 1987. "Anisotropic Filter Influence in Ultrasonic Nondestructive Examination of CCSS." Presented at the EPRI Seminar on "Cast Stainless Steel Inspection," January 8–9, 1987.

Rose JL, P Karpur and VL Newhouse. 1988. "Utility of Split Spectrum Processing in NDE." *Materials Evaluation* 46(1):114–122. Presented at the Fall 1986 ASNT Conference, October 1–3, 1986, New Orleans, Louisiana.

Saniie J and NM Bilgutay. 1986. "Quantitative Grain Size Evaluation Using Ultrasonic Backscattered Echoes." *Journal of Acoustical Society of America* 80(6):1816–1824.

Selby GP. 1987. "Ultrasonic Examination of Cast Stainless Steel Components." Presented at the EPRI Seminar on "Cast Stainless Steel Inspection," January 8–9, 1987.

Shankar R, P Jeong and R Williams. 1989. *Feature-Based Imaging for Cast Stainless Steel Components: 1987 and 1988 Field Examinations*. NP-6177, Research Project 1570-2, Electric Power Research Institute NDE Center, Charlotte, North Carolina.

Thompson RB. "Ultrasonic Inspection of Cast Stainless Steel"

Whitaker JS and TJ Jessop. November 1978. *Ultrasonic Detection and Measurement of Defects in Austenitic Stainless Steel – A Literature Survey*, Report No. 3576/1/78, The Welding Institute, London, England (in box provided by A. Diaz)

Williams PG. 1976. *Ultrasonic Testing of Austenitic Steels: A Selective Bibliography, 1958–1975.* Central Electricity Generating Board, Information Services, London.

Appendix B

CASS Network – Contacts in Industry, Government, and Academia for CCSS and SCSS

Appendix B

CASS Network – Contacts in Industry, Government, and Academia for CCSS and SCSS

Steve Doctor (no date) mentions two possible contacts—Edger I. Landerman of Westinghouse (412-374-4024) and Ed Kay of Sandusky (419-626-5340).

Table B.1. PNNL CCSS Networking List

Name Affiliation	Address	Telephone	Remarks
Robert Voigt Penn State University		814-863-7290	Teaching and research on foundry practices
R. D. Rishel		724-722-5073 rishelrd@ westinghouse.com	Rishel (1987) Formerly of Westinghouse; called back 6/12/08
Paula Freyer, Principle Engineer Materials Center of Excellence Westinghouse		412-256-1771	EPRI PWSCC meeting in Atlanta, June 11-14, 2007 – no help
Russ Reber, Vice President Forged Bar and Billet Business Group Carpenter Technology Corp. Specialty Alloys Operations	101 West Bern Street Reading, PA 19601 USA	610-208-3130	PSU QMM Board – no help
Joe Rose Penn State University		814-863-8026	Rose et al. (1987)
Edgar I. Landerman Westinghouse		412-374-4024	Doctor (no date)
E. T. Hughes D. C. Adamonis Westinghouse			Pade & Enrietta (1981)
Seth Swamy		724-722-6001	Bill Cherkowsky? @ Edger Landerman's Telephone
Peter Jeong EPRI NDE Center			Jeong (1987) Dexel PHD of Rose
Steve Doctor PNNL		509-375-2495	
Kamaljit (A) Ahluwalia EPRI (NJ)		973-396-2777	EPRI PWSCC Atlanta – to call back 6/10/08
Steven Todd IHI Southwest Technologies, Inc.		210-256-4107	EPRI PWSCC Atlanta – to call back 6/10/08
Kenneth Forlenza Georgia Power	Bin 10120 241 Ralph McGill Blvd NE Atlanta, GA 30308-3374	404-506-6243 kpforlen@ southernco.com	COR – he forwarded my request to Southern Nuclear 6/12/08
John R. Dillon, VP Engineering and Tech Services Robin Churchill Ed Kay Sandusky		503-228-2141 jrdillon@ escocorp.com 419-626-5340	Re: R. C. Voigt Re: Lee Aspaas

B.1 References

Doctor SR. No date. Notes from EPRI CCSS Workshop II.

Jeong YH. 1987. *An Ultrasonic Material State Classifier for Elastically Anisotropic Materials, Vol. 1, Appendix B, Metallurgical Aspects of the Grain Structure Formation*. Ph.D. Thesis Thesis, Drexel University, Philadelphia, Pennsylvania.

Pade ER and JF Enrietta. 1981. *Reliability of Ultrasonic Test Method for Detecting Natural Fatigue Cracks in Centrifugally Cast Stainless Steel Pipe*. WCAP-9894, Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

Rishel RD. 1987. "Ultrasonic Inspection of Cast Stainless Steel Materials." Presented at the EPRI Seminar on "Cast Stainless Steel Inspection," January 8–9, 1987.

Rose JL, A Tverdokhlebov, A Pilarski, K Balasubramaniam and D Diprimeo. 1987. "Anisotropic Filter Influence in Ultrasonic Nondestructive Examination of CCSS." Presented at the EPRI Seminar on "Cast Stainless Steel Inspection," January 8–9, 1987.

Appendix C

Foundries and Contacts for CCSS and SCSS

Appendix C

Foundries and Contacts for CCSS and SCSS

Table C.1 lists the foundries that were found in the references, personnel contacts, etc.; who may be casting, or have cast pipe suitable for application in primary pressure boundary of LWRs.

Table C.1. Stainless Steel Pipe and Component Foundries and Network

Foundry/Network Contact	Address	Telephone/Email	Remarks
ACIPCO American Cast Iron Pipe Co. American Centrifugal Ken Murphy	1501 31st Ave. North Birmingham, AL 35207	800-326-7717 205-325-7705 205-325-8193	R. C. Voigt M. Anderson, Web, De Garmo et al. (1997)
Atlas Foundry Ken Sandell	Tacoma, WA	253-475-4600	R. C. Voigt
Centrifugal Castings, Inc.	3320 Parkway Dr. Box 210 Temple, TX 76501-9703	800-999-9068 254-773-9068	Source=Web
Delta Centrifugal Corporation Roman Radon, metlrgst Mark Anderson,VPx470	P. O. Box 1043 Temple, TX 76503-1043	888-433-3100 524-773-8988	Source=Web
Duraloy Technologies, Inc.	120 Bridge St. Scottdale, PA 15683	724-887-5100	Source=Web
ESCO Engineered Products John Dillon Christopher Oldfellow	2141 NW 25th Ave., Portland, OR 97210	503-228-2141 jrdillon@escocorp.com chri.oldfather@escocorp.com	(1991) Rishel (1987)
FAM	France		Chopra (1991)
George Fischer Co.?			Chopra and Chung (1985), page 13; Chopra (1991)
Metal Tek International Wisconsin Centrifugal Phil Crouch	Waukesha, WI	262-544-7700	Source=Web R. C. Voigt
Metales Cenriugados Miguel Calderon	4ta Vidriera 1658 Col Reforma Monterrey, Nuevo Leon 64550 Mexico	(52-81)83744767	Source=Web
Miller Centrifugal Casting Co.	P. O. Box 456 Cecil, PA 15321-0456	724-745-0300	Source=Web
POLISFER		+7 (3412) 638-333	Source=Web
Sandusky Foundry & Machine Co. Ed Kay, G Michaels, Dr. W Stubblebine Christopher Reeve Brian Holzaephel Dir. of Operations John Rogers (history)	Sandusky, OH 44870-	419-626-5340 christopher.reeve@sanduskyintl.com brian.holzaephel@sanduskyintl.com Ext 327	Source = Doctor (no date), Pade & Enrietta (1981), & Web Rishel (1987)

Foundry/Network Contact	Address	Telephone/Email	Remarks
Spuncast Inc. Don Payne	W 6499 Rhine Rd. Watertown, WI 53094	920-262-6462	Source=Web
Techni-Cast	11220 So. Garfield Ave. Southgate, CA 90280	800-923-4585	Source=Web
U. S. Pipe and Foundry Jim Lambert Gerry Craft	 Birmingham, AL Union City, CA	866-341-7473 510-441-5834 510-282-8436 GACraft@USPIPE.com	Source = Curtis III (no date), Rishel (1987), & Web

C.1 References

Chopra OK. 1991. *Estimation of Fracture Toughness of Cast Stainless Steel During Thermal Aging in LWR Systems*. NUREG/CR-4513, ANL-90/42, R2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and HM Chung. 1985. *Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems – Annual Report October 1983 – September 1984*. NUREG/CR-4204, ANL-85-20, U.S. Nuclear Regulatory Commission, Washington, D.C.

Curtis III AE. No date. “Westinghouse Owners Group-Demonstration of Flaw Detection and Characterization Capabilities for Ultrasonic Inspection of Main Coolant Loop Welds.”

De Garmo EP, JT Black and RA Kohser. 1997. *Materials and Processes in Manufacturing*. 8th ed. Prentice Hall, Upper Saddle River, New Jersey. ISBN 0-02-328621-0.

Doctor SR. No date. Notes from EPRI CCSS Workshop II.

Pade ER and JF Enrietta. 1981. *Reliability of Ultrasonic Test Method for Detecting Natural Fatigue Cracks in Centrifugally Cast Stainless Steel Pipe*. WCAP-9894, Westinghouse Electric Corp., Pittsburgh, Pennsylvania.

Appendix D

PNNL CASS PISC Specimen (B-Series) Documentation

Appendix D

PNNL CASS PISC Specimen (B-Series) Documentation

Revised: 04/09/09

Note that most of the documents had the TUBECO JOB NO. 308001 hand written on each page.

APPENDIX C* – Material Furnished
by Tubeco, Inc.

I Loose Material
II Test Piece II
III Test Piece I

*Note, this is not Appendix C for this report.

Selected eight pages from the material furnished by Tubeco, Inc.

PNNL CASS PISC Specimens - CCSS-RRT and B-Series Fabrication Records:

Copies of a number of pages of documents pertaining to the fabrication of a nozzle by TUBECO, Inc. of 123 Varick Ave., Brooklyn, New York 11237 for Westinghouse P.O. 308001 in 1973 were obtained from Dr. Steven Doctor of PNNL, Applied Physics and Materials Characterization Sciences Group. Copies of pages pertinent to PNNL specimens discussed in this report are contained in Appendix D.

As determined from the TUBECO documents and discussions with PNNL scientists, a portion of a nozzle was fabricated from two centrifugal cast ASTM A351-CF8A stainless steel 27.5-in. (700-mm) ID pipes (heats), 11-ft (33.5-m) and 4.25-ft (13-m) long, respectively. One of the pipes was centrifugally cast by Sandusky Foundry and Machine Co. as heat number 144179 in about January of 1973, and copies of certifications are included in Appendix D. These two pipes were circumferentially welded together, and other pieces added to complete the nozzle. Subsequently, as mentioned in Bates et al. (1987), the 27.5-in. ID section was used to provide PNNL specimens with CCSS-RRT designations, nine of which were also designated as B-5XX (B-Series).

Thirteen of these specimens were circumferential sections of about 25 azimuthal degrees (about 170- to 180-mm chord length, 190-mm circumferential length,) and 400 mm in axial length cut from the nozzle weldment fabricated from the two 27.5-in. ID pipes. Note that Bates et al. (1987) reported that the PNNL CCSS-RRT specimens were fabricated from 845-mm OD, 60-mm wall thickness CCSS pipes butt-welded together. However, 845 mm OD minus the wall thickness of 60 mm equals 725 mm; which is 25 mm (1 in.) larger than the 700 mm (27.5-in.) written in the TUBECO Bill of Materials.

Apparently, one of the 27.5-in. pipes used in the nozzle had a single band of equiaxed grains and the other a single band of columnar grains, which resulted in 13 specimens with different grain structures on each side of the weld. This was discovered when the specimens were examined for grain structure.

Further, another weldment was also sectioned that had equiaxed grains on both sides of the weld, and which provided CCSS-RRT specimens 1 and 14 reported in Bates et al. (1987). Documents did not reveal which of the grain structures were in Sandusky heat number 144179.

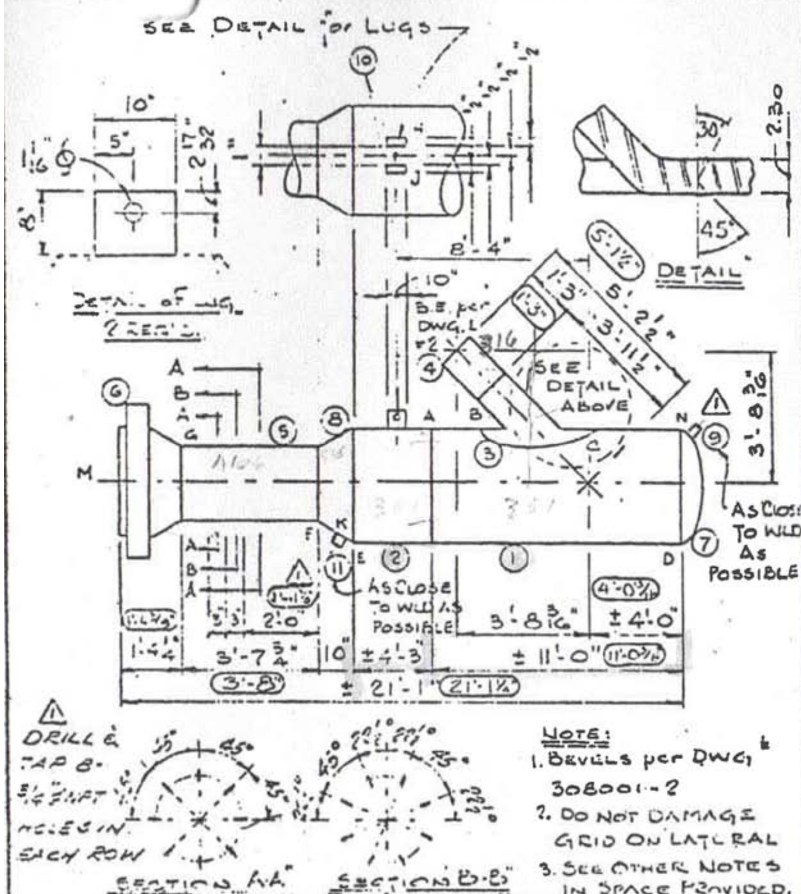
D.1 References

Bates DJ, SR Doctor, PG Heasler and E Burck. 1987. *Stainless Steel Round Robin Test: Centrifugally Cast Stainless Steel Screening Phase*. NUREG/CR-4970, PNL-6266, PISC III Report No. 3, U.S. Nuclear Regulatory Commission, Washington, D.C.

JOB NO. 308001

Legend (As Built Dimen's)

P.O. 308001-1



BILL OF MATERIALS, SHOP OPERATIONS and SERVICES

MTR NO. / HT. NO.	NO.	DESCRIPTION	COMPUTER CODE EQUIVALENT
		CUST'S MAT'L.	
3CC21 / 144179	1	1 Pc - 27½" I.D. x 11'-0 LG ST. STL PIPE	SA351-CF8A
AJ0108 / B-2647	2	1 Pc DITTO, EXCEPT 4-3" LG.	- SA351-CF8A
3H0513 / 59433-1	3	1 - 12" x 27½ I.D. - 45° CAST ST. STL. LAT'L	
		TUBECO MAT'L.	
3H0424 / J3443	4	1 Pc - 12" Sch 140 SMLS ST STL PIPE A376 T316	CUT FROM 3'-0" / TPO 10265
3H0339	5	1 Pc - 24" Sch 160 PIPE A-106 GR B	TPO 10247
3K0235 / ENKH	6	1 - 24" - 1500# R.F. W.N. FLG A-105 GR II (bore)	TPO 10272
3LD105 / H-71825	7	1 - 33" O.D. x 2¾ M.W. DISHED HD A516 GR 70	TPO 10275
3LD250 / TPHH	8	1 - 32" O.D x 24" ³/₁₆₀ CONC. RED'R (A516 GR 70)	TPO 10272
3L0396	9	1 - ½" x 6" LG ³/₁₆₀ NIPPLE T.O.E. A106 GR B	ATPO 10341
3H0368	10	2 Pc's 10" x 8" x ½" THK P. A285 [SAW FROM 5' x 10" W]	TPO 10246
3L0395	11	1 - ½" x 6" LG ³/₁₆₀ NIPPLE T.O.E. A 106 GR B	

FIX. & PROT. (Yes / No)
- Coat / Paint:
- Vinyl Covers Caps
- Plywood Flg. Covers
- Metal Covers
- Metal Covers w/Wood ✓
- Others:

SERV'S per PROCED'E
- Cement Line
- Rubber L C
- Pickle
- Galvanize
- Blast in Out
- Demin. Wash
- Others:

MATERIAL SPECIFICATIONS

ITEM	ASME- ASTM
Pipe: Smls Wld'd Sch.	SEE B/M
Flange(s)	
Fitting(s)	
Coupling(s)	
Plate	
Others:	

REVISIONS

No.	Description	T.No	By	Date
1	HOLE ON DRILLING RELEASED, RELOCATED NOZZLE ITEM 5, AND ADDED NOZZLE ITEM 11	✓	W	10/...
2	ADDED SHOP COMMENTS	11/2	SPM	11/1/72

PRODUCTION PROCEDURES
- Weld. End Prep. PER DWG 308001-2
- Weld. Proced's SEE TRAVELLER
- Weld. Mat'ls SEE WELD PROCEDURES
- (Insert Root Pass with C.I.)
- (B.R's Split Wld'd Solid Tapered)
- Bending N/A
- Heat Treatment N/A

N.D.E. PROCEDURES / INSP
- Delta Ferrite 5% Min
- Hydrostatic NONE
- RT B. WLD. R
- RT Br. WLD. R
- RT B. WLD. 100% ✓
- RT Br. WLD. 100% ✓
- UT B. WLD.
- UT Br. WLD.
- UT BEND
- UT THICKNESS
- PT B. WLD ✓
- PT Br. WLD. ✓
- PT BEND
- MT B. WLD.
- MT Br. WLD.
- MT BEND

CODE REF.

Cust. Spec. No. G-676643
System R.C.

NOTES
1. WELDS A, B & C STAINL. ST. WELDS D & E DISSIMILAR METALS
2. WELDS F, G, H, J, K, CARB. STEEL
3. SEE TRAVELLER

CUSTOMER: WESTINGH. ELECTRIC CORP. WNES

PROJECT: TEST-PIECE

Cust. Ord. No. H1871B1A
Ref. Dwg. No.

MARKINGS: Std. ✓
OTHERS:

Dwn. By W Date ...
Chk'd. By JDS Date ...

TUBECO INC
123 VARICK AVENUE BROOKLYN, N.Y. 11237

PC. MK. NO. T.P-1

JOB NO. 308001

DWG. NO. 001 REV. 2

TUBECO JOB NO 308001

SANDUSKY CENTRIFUGAL CASTINGS
FOUNDRY & MACHINE CO.

TWX: 810-492-2624
TELEX: 980-563

SANDUSKY, OHIO
44870

PHONE: (419) 626-5340
CABLE: SANCAST

Documentation Package #2 - PRW

Westinghouse Purchase Order 546-CRC-174721-VN

Items covered:

Quantity	W Item No.	SFM Heat No.	SFM Shop Order
1	1	144179	95327

Section A

Laboratory tests were performed on Heat 144179 with the following results: (Reference Spec. ASTM A-351 Gr. CF-8A)

1. Chemical Analysis, %

0.06	Carbon
0.68	Manganese
1.17	Silicon
20.42	Chromium
8.58	Nickel
0.02	Phosphorus
0.02	Sulphur
0.07	Cobalt
17.4	Delta Ferrite

2. Mechanical Tests, Transverse

At Room Temperature:

Yield Strength, psi 0.2% offset 43,950
Tensile Strength, psi 81,250
Elongation, % in 2" 48

At 650°F:

Yield Strength, psi 0.2% offset 23,100

8042

JTH:dmn

1.

Order 546-CVG-174721-VN Spin PRW RCPCCP Serial 144179

3. Etch Test

Test performed per contract with acceptable results.

Laboratory tests in Section A have been completed with approved results.

G. J. Deffenbaugh
Laboratory Manager

Date 1-5-73

Section B

1. Radiography

Completed per contract with acceptable results including reradiography of major repair welds as required. Repair chart and reader sheets attached.

2. Liquid Penetrant

Completed per contract with acceptable results.

3. Dimensional Check

Completed with acceptable results, charts attached.

4. Shop Traveler

Copy attached to indicate proper completion of manufacturing and test applications.

Tests and procedures in Section B have been completed with acceptable results.

12473

W. Mehnert
Inspection Manager

Date 2-20-73

JTH:dmn

Order 546-CVG-174731-VM - Spin PRW RCPCCP Serial 144179

Section C

1. Heat-Treatment

Performed per contract. Heat-treat log attached.

2. Required Guarantees

The successful completion of the tests in Sections A and B are the basis of the supplier's required guarantee that the minimum yield strength of the pipe furnished shall be 19,850 psi at 650°F and that the pipe furnished is capable of withstanding a hydrostatic pressure test of 3,105 psig at 60-90°F held for 30 minutes per inch of wall thickness without resultant damage or leakage.

The documentation package has been reviewed. The material covered herein is approved and released subject to Westinghouse release.

J. T. Herlihy
Manager of Research
and Quality Control

Date 2-27-73

JTH:dmn
Attachments

Order 546-CVG-174721-VN Spin PRW RCPCCP Serial 144179

TUBECO JOB NO 308001

ZU-203 S.&T.D. CERTIFICATE OF PHYSICAL PROPERTIES

Steel and Tubes Division

Date December 21, 1971

To Whom It May Concern:

We do hereby certify that the following mechanical property values have been determined by standard testing procedures.

Customer: Westinghouse Electric Corporation Atomic Power Division

Customer's Order No. 546-CFW-86013-VN

Material: ASTM A-351 Grade CF8A

Our Order No. IPD-02515

Lot No.	Heat Number	Date Shipped	Yield Strength	Ultimate Strength	Elong. %	% R. A.	Brinell Hardness
				ROOM TEMPERATURE			
	B-2647		42,300	83,400	55.0	73.2	228
	B-2659		39,800	77,611	59.0	73.4	202
	B-2759A		40,460	84,915	49.0	69.0	196
				ELEVATED TEMPERATURE (650°F)			
	B-2647		22,400	64,250	46.0	59.4	
	B-2659		20,000	58,500	43.5	59.8	
	B-2759A		22,200	62,000	41.5	57.8	

12-21-71

3010302

Sworn and subscribed before me this day of ... 1971

Notary Public

NOTARY PUBLIC OF NEW JERSEY

My Commission ...

ON THE STATE ...

Chief Inspector, I.P.D.

PAGE ___

TUBECO INC. 123 VARICK AVENUE, BROOKLYN, N.Y. 11237

RADIOGRAPHY REPORT

DATE 12-26-73

JOB-NO: 308001		ASME: 1 (3) 8 / OTHER SPECS:		MATERIAL SPEC. 5/11 33 1	
MATERIAL THICK. 2 1/2 "	MATERIAL LENGTH OR WIDTH 32 " OD	USAS-B-31.7 31.1.0 / API-1104 /		TYPE SEAM BUTT-WELD	
ISOTOPE IR 192	DIA X LENGTH 2 X 2MM; CURIES	DISTANCE IN; TIME MIN	AA T M 55 D-7 /	FILM SIZE 4.5X10 4.5X17 (7X17)	FILM TECH. [X] DOUB
ISOTOPE CO 60	DIA X LENGTH 3mm Dia; CURIES 5.4	DISTANCE 15 IN; TIME 30 MIN	TOTAL UNSHARPNESS MM	FILM PROCESSING 8 MIN - 68 F	RADIOGRAPHER TUBECO NDT

FITTING, SEAM OR JOINT NUMBER	FILM INTERVAL NUMBER	PENETRAMETER SIZE ASME	ACCEPT.	REJECT	SLAG	POROSITY	CRACK	LACK OF PEN.	LACK FUSION	UNDERCUT	SURFACE	BURN-THRU	SUCK-BACK	TUNGSTEN	BEAD EDGE	DATE FILM EXPOSED	w/c=within code, st =start stop, ic =icicle, cbr=curled backing ring, b/t=burn thru, nad=no apparent defects, sb=suckback, br=backing ring
TY-1	1-2	30/35	✓													12-26-73	
C	2-3	|	✓														
	3-4	|	✓														
	4-5	|	✓														
	5-6	|	✓														
	6-7	|	✓														
	7-8	|	✓														
	8-9	|	✓														
	9-10	|	✓														
	10-1	↓	✓														

Customer Acceptance

By ________ Date ________

Interpreted By [signature] Date 12-27-73

SHIM THICKNESS 1/2

LEAD SCREENS .010

D.8

TUBECO INC. 123 VARICK AVENUE, BROOKLYN, N.Y. 11237

RADIOGRAPHY REPORT

DATE 1-4-74

JOB-NO: 308001		ASME 1 3 8 / OTHER SPECS:		MATERIAL SPEC: S/A 351
MATERIAL THICK. 2 1/2 "	MATERIAL LENGTH OR WIDTH 32 "OD	USAS-B-31.7 31.1.0 / API-1104 /		TYPE SEAM BUTT-WELD
ISOTOPE IR 192	DIA & LENGTH 2 X 2MM; CURIES -; DISTANCE IN; TIME MIN	AA T M 55 D-7 /	FILM SIZE 4.5X10 4.5X17 (7X17)	FILM TECHNIQUE [X] DOUBLE
ISOTOPE CO 60	DIA & LENGTH 3mm Dia; CURIES 5.4; DISTANCE 16 IN; TIME 40 MIN.	TOTAL UNSHARPNESS MM	FILM PROCESSING 8 MIN - 68 F	RADIOGRAPHER TUBECO NDT

FITTING, SEAM OR JOINT NUMBER	FILM INTERVAL NUMBER	PENETRAMETER SIZE ASME	ACCEPT.	REJECT	SLAG	POROSITY	CRACK	LACK OF PEN.	LACK FUSION	UNDERCUT	SURFACE	BURN-THRU	SUCK-BACK	TUNGSTEN	BEAD EDGE	DATE FILM EXPOSED	w/c=within code; st =start stop; ic =icicle; cbr=curled backing ring; b/t=burn thru; .nad=no apparent defects; .sb=suckback; .br=backing ring
T-1	1-2	30/35	✓													1-4-74	N.A.D.
3	2-3	|															N.A.D.
D	3-4	|															N.A.D.
	4-5	|	✓														N.A.D.
	5-6	|	✓														N.A.D.
	6-7	|	✓														N.A.D.
	7-8	|	✓														N.A.D.
	8-1	↓	✓														N.A.D.

Customer Acceptance

By ______ Date ______

Interpreted

By [signature] Date 1-7-74

SHIM THICKNESS 1/2

LEAD SCREENS .010

TUBECO INC. 123 VARICK AVENUE, BROOKLYN, N.Y. 11237

TEST REPORT PT/MT

Reported By JAL

Date 12·7·73

PROJECT	DESCRIPTION OF PART, COMPONENT OR SYSTEM	MATERIAL SPEC.
WestingHouse Exp. Test	Tubeco 308001	SA351 CF8A

MATERIAL THICKNESS	MATERIAL LENGTH OR WIDTH	ACCEPTANCE STANDARD	GOVERNING SPECIFICATION	AREA COVERED BY TEST
2¼"	27½" ID	T-200-4	Sec III Mon	See Below

LIQUID PENETRANT ☒ — SURFACE CONDITION: Good — PENETRANT TYPE & MANUFACTURER: ☐ WATER WASHABLE ☐ POST-EMULSIFYING ☒ SOLVENT-REMO SKL-S

DEVELOPER TYPE & MANUFACTURER: ☐ DRY ☒ WET Magnaflux SKD-S — PROCEDURE USED: Tubeco T-200-4 — TEST PERFORMED BY: J. Lopez Level II

MAGNETIC PARTICLE ☐ — SURFACE CONDITION — METHOD & TYPE OF MEDIUM: ☐ DRY ☐ WET ☐ FLUORESCENT — MAGNETIZATION: ☐ CIRCULAR ☐ LONGITUDINAL

PROD SPACING & AMPERAGE — DEMAGNETIZED — CURRENT: ☐ AC ☐ DC — PROCEDURE USED — TEST PERFORMED BY

PIECE OR JOINT NUMBER	INDICATE SIZE AND LOCATION (Use Sketch If Necessary)	ACCEPT	REJECT	INFO. ONLY	BRIEFLY DESCRIBE INDICATIONS
TP-1	WPS-8				
C 5	Liquid Pen Exam After 1½" of Weld Build-up on O.D Side	X			NAD 12·7·73
6	Liquid Pen Exam After 2" of Weld Build-up on O.D Side	X			NAD 12·11·73
7	Final Cover Pass After Dressing	X			NAD 12·17·73

D.10

TUBECO INC. 123 VARICK AVENUE, BROOKLYN, N.Y. 11237

TEST REPORT PT/MT

Page 1 of 1

Reported By JA'L

Date 11-19-73

PROJECT: WesTingHouse Exp Test		DESCRIPTION OF PART, COMPONENT OR SYSTEM: TUBECO 308001		MATERIAL SPEC.: SA351 CF8A
MATERIAL THICKNESS: 2¼	MATERIAL LENGTH OR WIDTH: 27½	ACCEPTANCE STANDARD: T-200-4	GOVERNING SPECIFICATION: Sec III Mod	AREA COVERED BY TEST: CuT out
LIQUID PENETRANT ☒	SURFACE CONDITION: Good	PENETRANT TYPE & MANUFACTURER: ☐ WATER WASHABLE	☐ POST-EMULSIFYING	☒ SOLVENT-REMO SKL'S
DEVELOPER TYPE & MANUFACTURER: ☐ DRY ☒ WET MagnaFlux		PROCEDURE USED: TUBECO T-200-4		TEST PERFORMED BY: [illegible] Lozzer LEVEL II
MAGNETIC PARTICLE ☐	SURFACE CONDITION	METHOD & TYPE OF MACHINE: ☐ DRY ☐ WET ☐ FLUORESCENT	MAGNETIZATION: ☐ CIRCULAR	☐ LONGITUDINAL
PROD SPACING & AMPERAGE	DEMAGNETIZED	CURRENT: ☐ AC ☐ DC	PROCEDURE USED	TEST PERFORMED BY

PIECE OR JOINT NUMBER	INDICATE SIZE AND LOCATION (Use Sketch If Necessary)	ACCEPT	REJECT	INFO. ONLY	BRIEFLY DESCRIBE INDICATIONS
TP-1	PREPARED CUT OUT SEQUENCE #60				
TRM 1	1 Liquid Pen Test		X		11-19-73
	2 REPEAT SEQUENCE #70 SMALL indications		X		11-20-73
	3 REPEAT SEQUENCE #70 No indications	X			11-28-73 NAD

Appendix E

Westinghouse Data on 70 Heats of Cast Pipe and 70 Heats of Cast Fittings (Elbows)

Appendix E

Westinghouse Data on 70 Heats of Cast Pipe and 70 Heats of Cast Fittings (Elbows)

Notes on material certs:

70 heats of cast pipe and 70 heats of cast fittings in this random survey.

In general, no plants excluded or included for any particular reason.

2,3 and 4 loop plants represented. Roughly 15 plants sampled.

Material is primary loop cast stainless piping and cast stainless fittings.

Concentration on CF8M grade.

On piping certs, 38 of 70 have chemistry and mechanical test data, the rest, chemistry only.

For cast fittings, all have chemistry and some mechanical certs.

Δ ferrite is shown on CF8A certs only.

Cast Fittings are 60 heats CF8M and 10 heats CF8A.

Cast fittings are primarily one vendor, with Cast piping split pretty evenly between 2 vendors.

Data is not segregated by hot and cold leg piping and fittings, all are represented in the survey.

Pipe Vendors
U.S. Pipe = Ref. 1
Sandusky = Ref. 2

Elbow Vendors
ESCO = Ref. 1
Italian Foundry = Ref. 2

Section XI TG CSS

Component: Primary Loop CSS Piping

Basic Westinghouse PWR CSS Properties Data
Material: ASTM A351 CF8M   Source: Random Sampling of Heats from 15 Plants
Manufacturing Period – 1969 to 1976   Vendors - 2

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong	Elong. 650° F	Ferrite %	Brinell	Ref. Heat/ Vendor
.07	.7	.020	.012	.86	2.66	19.65	9.8	.036	38.9K	24.8K	82.31K	63.9K	45.5	37.5		217	1/1
.04	.74	.014	.014	.91	2.76	20.1	9.74	.05									2/1
.04	.74	.014	.014	.91	2.76	20.1	9.74	.05									3/1
.06	.75	.013	.012	1.02	2.62	20.17	9.8	.088									4/1
.05	.75	.013	.012	1.02	2.62	20.17	9.75	.088									5/1
.06	.73	.012	.015	.93	2.66	20.92	10.06	.020									6/1
.06	.67	.016	.72	.98	2.66	20.7	9.8	.033									7/1
.06	.75	.016	.010	.98	2.8	20.7	9.4	.048									8/1
.07	.75	.016	.010	.98	2.66	20.0	9.5	.054									9/1
.05	.78	.014	.011	.96	2.84	19.57	9.9										10/1

E.4

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong	Elong. 650˚ F	Ferrite %	Brinell	Ref. Heat/ Vendor
.06	.78	.01	.011	.96	2.84	19.57	9.9										11/1
.03	.76	.01	.012	1.01	2.6	20.4	9.85										12/1
.05	.79	.01	.014	.96	2.73	20.2	9.75										13/1
.06	.67	.01	.012	.91	2.76	20.7	9.8	.03									14/1
.05	.75	.01	.012	1.02	2.62	20.17	9.75	.08									15/1
.06	1.21	.02	.03	.68		20.2	8.0	.05	47.1K	26.1K	82.5K		56.5		19.7 (1)		16/2
.06	1.44	.03	.02	.65		20.8	8.3	.05	48.4K	24.45K	84.65k		54		23.5 (1)		17/2
.06	1.3	.02	.03	.70		20.7	8.3	.05	49.3K	24.8K	82.65k		48		20 (1)		18/2
.06	1.48	.02	.03	.69		20.5	8.3	.05	47.1K	24.1K	85.2K		49		21.4(1)		19/2
.06	1.33	.02	.04	.72		20.3	8.2	.04	46.5K	25.6K	85.7K		59.5		19.7 (1)		20/2

Notes: (1) Δ Ferrite Schaeffler diagram

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong	Elong. 650° F	Ferrite %	Brinell	Ref. Heat/ Vendor
.06	1.35	.02	.04	.71		20.8	8.3	.05	45.3K	27.1K	84.15K		56		19.7		21/2
.06	1.37	.02	.04	.65		20.6	8.2	.03	43.35K	27K	84.45K		53		22.1		22/2
.06	1.4	.02	.04	.75		20.9	8.5	.04	48.1K	26.85K	85K		52.5		20.0		23/2
.05	1.25	.02	.03	.6		20.8	8.4	.04	43.9K		85.5K		58				24/2
.07	1.25	.02	.03	.71		20.7	8.5	.02	42.45K		85.5K		54				25/2
.05	1.36	.02	.04	.73		21	8.8	.04	43.95K		85.9K		50.5				26/2
.05	1.29	.02	.04	.75		20.7	8.6	.03	40.35K		86.25K		55				27/2
.06	1.28	.02	.03	.74		20.4	8.7	.02	38.7K		83K		54.5				28/2
.07	1.14	.02	.04	.94		20.6	8.5	.01	41.85K		84.5K		54.5				29/2
.05	1.3	.02	.03	.67		20.3	8.6	0.3	41.6K		82.9K		60				30/2

Notes: (1) Δ Ferrite Schaeffler diagram

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong	Elong. 650° F	Ferrite %	Brinell	Ref. Heat/ Vendor
.06	1.17	.02	.02	.63		20.4	8.7	.02	38.85K		77.5K		52				31/2
.07	1.38	.02	.03	.73		20.5	8.8	.04	38.9K		81.45K		50				32/2
.06	.79	.02	.02	.91	2.79	20.55	9.96	.04									33/1
.04	.72	.02	.01	.93	2.94	20.95	9.6	.02									34/1
.05	.84	.02	.01	.97	2.82	20.31	9.8	.14	39.46K	22K	80.92K	65.5	45	41.5			35/1
.05	.9	.02	.01	.98	2.85	20.89	9.66	.03	42.45K	23.6K	80.91K	68K	41	44			36/1
.06	.78	.02	.02	.93	2.71	20.23	10.26	.05	37.96K	20.9K	78.42K	61.5K	54	44			37/1
.06	1.24	.02	.02	.68		20.6	8.4	.05	46.5K	25.2K	84.25K		54		19 (1)		38/2
.04	1.16	.02	.02	.67		21.0	8.5	.05	47.1K	25.2K	82.5K		53		24.5 (1)		39/2
.04	1.27	.01	.02	.75		20.8	8.5	.05	49.8K	24.6K	83.75		57		24.5 (1)		40/2

Notes: (1) Identified as Δ Ferrite on cert.

E.7

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong	Elong. 650° F	Ferrite %	Brinell	Ref. Heat/ Vendor
.05	.78	.02	0.2	.78		20.3	8.9	.05	42.6K	24K	79.5K		56		15.7(1)		41/2
.06	1.11	.01	.02	.73		20.9	8.5	.05	43.8K	25.5K	83.5K		52.5		20 (1)		42/2
.05	.92	.02	.02	.74		20.9	8.6	.05	46.5K	22.95K	80.5K		50		19.0 (1)		43/2
.06	1.22	.02	.02	.73		20.8	8.5	.05	46.5K	24. 0K	80.5K		47		19.5 (1)		44/2
.06	1.04	.03	.03	.65		19.9	8.5	.01	38.55k		79.25K		66				45/2
.06	1.45	.02	.03	.71		20.4	8.3	.01	44.4K		81.25K		49				46/2
.05	1.44	.02	.03	.73		20.4	8.5	.04	40.65K		82.55K		55				47/2
.07	1.36	.02	.03	.71		20.6	8.4	.03	42.3K		80.05K		43.5				48/2
.06	1.39	.02	.03	.72		20.4	8.5	.03	42.0K		78.15K		46.5				49/2
.05	1.23	.02	.03	.55		20.9	8.9	.01	42.3K		83.0K		57				50/2

Notes (1) Identified as Δ Ferrite on cert

E.8

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong	Elong. 650˚ F	Ferrite %	Brinell	Ref. Heat/ Vendor
.05	1.41	.02	.03	.76		20.6	8.5	.01	42.05K		83.15K		56				51/2
.04	1.52	.02	.02	.59		20.6	8.5	.01	42.55K		84.45K		44				52/2
.06	1.26	.02	.03	.65		20.2	8.3	.03	41.45K		85.65K		58.5				53/2
.05	1.21	.02	.03	.6		20.5	8.8	.01	39.6K		83.0K		57				54/2
.056	.62	.02	.02	.78	2.75	21.0	9.7										55/1
.06	.66	.03	.02	.87		21.0	9.45										56/1
.06	.07	.02	.01	.86	2.61	20.4	9.86	.03									57/1
.06	.71	.02	.02	.98	2.66	20.4	9.9	.02									58/1
.08	.71	.01	.01	.93	2.62	20.3	9.76	.02									59/1
.04	.72	.01	.01	.9	2.74	20.4	9.96	.01									60/1

Notes

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong	Elong. 650° F	Ferrite %	Brinell	Ref. Heat/ Vendor
.06	.72	.02	.01	.94	2.71	20.4	9.75	.022									61/1
.06	.73	.02	.2	.93	2.7	20.92	10.0	.020									62/1
.06	.68	.02	.01	.91	2.61	20.0	9.8	.024									63/1
.05	.79	.020	.01	.92	2.78	20.12	9.75	.032									64/1
.05	.79	.020	.011	.92	2.78	20.12	9.75	.03									65/1
.07	.76	.02	.01	.99	2.75	20.67	9.81	.05									66/1
.05	.79	.02	.011	.92	2.78	20.12	9.75	.032									67/1
.04	.69	.02	.02	.90	2.66	19.55	9.8	.02									68/1
.06	.78	.02	.02	.98	2.73	19.8	9.61	.05									69/1
.05	.78	.02	.01	.98	2.79	20.52	9.81	.13									70.1

Notes

Section XI TG CSS

Component: Primary Loop CSS Elbows

Basic Westinghouse PWR CSS Properties Data
Material: ASTM A351 CF8A and CF8M   Source: Random Sample of Heats from 15 Plants
Manufacturing Period – 1967 to 1976   Vendors - 2

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.05	1.33	.004	.024	.42		19.83	8.75	.07	39.15K		88.0K		64	69	17		1/1 CF8A
.06	1.38	.001	.030	.69		20.86	9.64	.09	39.55K		79.65K		47	73	14		2/1 CF8A
.06	1.23	.008	.027	.76		20.6	8.9	.11	39.4K		82.35		68	72	16		3/1 CF8A
.06	1.22	.012	.038	.86	3.06 (2)	19.62	9.83	.10	48K		88K		52	65			4/1 CF8M (3)
.05	1.25	.011	.038	.91	3.0	19.83	10.31	.19	43.5K		86.5K		48	65			5/1 CF8M (3)
.06	1.25	.013	.035	.76	2.84	18.92	9.34	.10	45K		87.5K		52	70			6/1 CF8M (3)
.06	1.26	.008	.038	.90	2.82	19.31	9.64	.13	42K		86.5K		58	71			7/1 CF8M (3)
.06	1.09	.007	.036	.77	2.82	19.11	9.65	.13	42K		85.5K		71	73			8/1 CF8M (3)
.05	1.25	.012	.034	.85	3.0	19.4	9.3	.10	47.25K		89.25K		54	69			9/1 CF8M (3)
.08	1.2	.007	.04	.87	2.92	19.48	9.49	.14	48K		90K		51	64			10/1 CF8M (3)

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) High value but accepted
(3) Designated ASTM A351-65 GR CF8M

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.05	1.31	.007	.04	.84	2.82	19.3	9.75	.12	45k		88k		55	69			11/1 CF8M (2)
.07	1.26	.010	.04	.92	2.87	20.82	9.69	.14	55.5k		96.5k		42	67			12/1 CF8M (2)
.07	1.2	.007	.034	.84	2.87	19.36	9.48	.14	46.5k		89k		45	67			13/1 CF8M (2)
.07	1.24	.010	.037	.92	2.89	20.15	9.5	.16	49.5k		91k		46	63			14/1 CF8M (2)
.06	1.25	.007	.026	.52		19.79	8.88	.10	41.35k		86.2k		58	70	16.7		15/1 CF8A
.06	1.17	.010	.024	.77		20.08	9.0	.10	35.7k		81.2k		61	73	12.0		16/1 CF8A
.06	1.31	.005	.025	.86		20.01	8.51	.10	38.05k		83.2k		65	75	15.0		17/1 CF8A
.05	1.35	.010	.025	.76		19.48	8.46	.12	35.6k	24.1k	81.85k	61.4k	60/40 (3)	71/62 (3)	15.6		18/1 CF8A
.06	1.34	.010	.024	.61		20.6	8.64	.11	38.8k		83.95k		63	71	16.0		19/1 CF8A
.08	1.23	.010	.036	.83	2.69	20.17	9.10	.10	54k		96k		50	67			20/1 CF8A

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M
(3) Room temp and 650˚F

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.06	1.22	.007	.039	.84	2.84	13.63	9.78	.12	40.5K		85K		58	70			21/1 CF8M (2)
.05	1.48	.007	.04	.95	2.9	20.16	9.64	.11	49.5K		92.5K		46	64			22/1 CF8M (2)
.08	1.29	.008	.037	.99	2.96	19.65	9.67	.12	51K		91.5		45	68			23/1 CF8M (2)
.06	1.13	.007	.038	.85	2.95	19.4	9. 7	.16	48K		88K		50	65			24/1 CF8M (2)
.05	1.21	.008	.038	.83	2.89	18.76	9.75	.12	42K		86.5K		55	69			25/1 CF8M (2)
.07	1.29	.008	.04	1.01	3.0	19.66	9.68	.14	46.5K		89K		54	71			26/1 CF8M (2)
.06	1.28	.011	.023	.68		19.65	8.65	.10	36.2K	23.4K	79.8K	62.4K	63/44 (3)	72/62 (3)	13.7		27/1 CF8A
.08	1.27	.010	.030	.76		20.98	8.49	.10	41.25K		86.6		55	66	16		28/1 CF8A
.05	1.21	.010	.026	.73		19.52	9.09	.10	36.1		78.7		69	73	13		29/1 CF8A
.05	1.28	.010	.022	.87		19.99	8.84	.10	40.3		83.1		59	72	15		30/1 CF8A

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M
(3) Room Temp. and 650 F.

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650°F	Ultimate PSI	Ultimate PSI @650° F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.05	1.42	.013	.037	.93	2.95	19.39	9.83	.17	44.25		86.5K		52	70			31/1 CF8M(2)
.08	1.25	.008	.037	.93	2.95	19.15	9.78	.18	37.5K		77K		55	73			32/1 CF8M(2)
.08	1.29	.011	.037	1.08	2.84	19.29	10.02		35.8K		76.1K		61	72			33/1 CF8M(2)
.06	1.21	.001	.036	.84	2.74	20.02	10.70		34.6K		73.7K		57	68			34/1 CF8M(2)
.06	1.46	.004	.034	.81	2.36	19.29	9.62		44K		89.7K		57	72			35/1 CF8M(2)
.07	.83	.004	.035	.92	2.30	19.6	9.54	.15	45K		85K		57	71			36/1 CF8M(2)
.06	.86	.004	.033	.60	2.14	18.65	9.69	.19	35.2K		73.4k		53	74			37/1 CF8M(2)
.05	.84	.004	.033	.60	2.16	19.67	9.55	.14	42.1K		84.2K		63	70			38/1 CF8M(2)
.06	.83	.004	.033	.74	2.19	18.25	10.11	.05	32K		71K		59	73			39/1 CF8M(2)
.06	1.16	.001	.025	.49		19.46	8.39	.09	42.25K		86.3K		62	64	14		40/1 CF8A

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.05	1.14	.012	.034	.63	2.08	18.52	9.25	.10	41.93K		86.7K		60	73			41/1 CF8M(2)
.05	.76	.005	.032	.67	2.78	19.56	9.58	.13	49.5K		84.25K		50	68			42/1 CF8M(2)
.05	1.08	.008	.033	.70	2.16	19.31	9.59	.16	45.48K		85.15K		55	70			43/1 CF8M(2)
.07	1.04	.003	.034	.70	2.11	19.10	9.35	.15	42.7K		84.6K		59	73			44/1 CF8M(2)
.06	1.25	.010	.037	.59	2.19	18.4	4.36	.16	36.55K		80.65K		57	63			45/1 CF8M(2)
.05	.97	.002	.034	.73	2.3	18.5	9.07	.19	42.6		83.2		61	74			46/1 CF8M(2)
.06	1.11	.003	.033	.67	2.07	18.31	9.08	.14	42.8K		88.4		61	73			47/1 CF8M(2)
.060	1.11	.004	.034	.91	2.05	18.84	18.84	.13	42.3K		83.5		58	70			48/1 CF8M(2)
.05	1.21	.009	.036	.87	2.85	19.52	9.7	.15	46.5K		88K		56	70			49/1 CF8M(2)
.07	1.03	.007	.036	.82	2.88	18.88	9.6	.13	39K		78K		58	68			50/1 CF8M(2)

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.07	1.34	.012	.038	.89	2.92	19.45	9.51	.17	43.5K		87K		50	70			51/1 CF8M(2)
.07	1.39	.006	.037	1.13	2.92	17.64	10	.11	42K		82.5K		37	71			52/1 CF8M(2)
.06	1.2	.01	.037	.87	2.99	19.51	9.68	.14	48K		88.5K		45	65			53/1 CF8M(2)
.06	1.45	.009	.037	.82	2.38	19.48	9.53	.15	45K		88.5K		50	64			54/1 CF8M(2)
.06	1.05	.004	.032	.93	2.26	19.73	9.27	.17	43.95K		87.9K		52	71			55/1 CF8M(2)
.06	.62	.004	.036	.76	2.47	20.67	9.57	.17	48.7K		88.2K		49	69			56/1 CF8M(2)
.06	.82	.003	.032	1.12	2.2	18.45	9.26	.13	40.9K		83.4K		62	71			57/1 CF8M(2)
.050	.97	.002	.034	.73	2.3	18.5	9.07	.11	42.6K		83.2K		61	74			58/1 CF8M(2)
.059	1.11	.003	.033	.67	2.07	18,5	9.08	.14	42.8		88.4		61	73			59/1 CF8M(2)
.060	1.14	.004	.034	.91	2.05	18.84	9.26	.13	42.3		83.5		58.	70			60/1 CF8M(2)

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M

C	Si	S	P	Mn	Mo	Cr	Ni	Co	Yield PSI	Yield PSI @650˚F	Ultimate PSI	Ultimate PSI @650˚ F	Elong %@2"	Elong. %Red	Ferrite % (1)	Brinell	Ref. Heat/ Vendor/ grade
.08	.83	.039	.040	1.01	2.79	20.3	10.10	.13	37.11K		76K		61	66			61/2 CF8M(2)
.06	1.07	.003	.033	.64	2.13	18.8	10.41		31.7K		71.7K		69	77			62/1 CF8M(2)
.07	1.00	.010	.034	1.10	2.15	19.57	9.62	.15	40.8K		81.8K		48	72			63/1 CF8M(2)
.06	1.12	.005	.033	.70	2.08	18.67	9.29	.15	41.43K		85.95K		60	73			64/1 CF8M(2)
.04	1.08	.008	.035	1.18	2.10	19.14	9.36	.13	43.78K		85.3K		57	70			65/1 CF8M(2)
.08	1.38	.004	.030	1.18	2.10	19.14	9.36	.13	45.1K		85.2K		49	61			66/1 CF8M(2)
.08	1.24	.004	.030	1.18	2.10	19.14	9.36	.13	50.02K		80.6K		47	68			67/1 CF8M(2)
.06	.90	.007	.034	.90	2.24	19.61	9.42	.16	43.8K		85.6K		56	71			68/1 CF8M(2)
.07	.74	.007	.035	.79	2.34	19.94	9.38	.17	47K		86.5K		51	70			69/1 CF8M(2)
.06	1.12	.005	.033	.70	2.08	18.87	9.29	.15	55.5K		96K		47	67			70/1 CF8M(2)

Notes (1) Ferrite calculation by Schoefer modification of Schaeffler diagram.
(2) Designated ASTM A351-65 GR CF8M

Appendix F

Correspondence

Appendix F

Correspondence

Print

Read

From "CLAYTON RUUD" <cor1@psu.edu> ⊕

To aaron.diaz@pnl.gov ⊕ , Michael.Anderson@pnl.gov ⊕

Subject Scheduling PNNL Visit to Sandusky

Date Fri, Oct 31, 2008 01:05 PM

CC Brian.Holzaepfel@sanduskyintl.com ⊕

Safe View On [Turn Off] What is "Safe View"?

Aaron and Mike, I called Brian Holzaepfel at Sandusky Machine and Foundry this morning to make sure he received my email of October 27 and he acknowledged that he had but has been on travel. He said that Sandusky will be pouring AISI 316 stainless steel the weeks of the 3rd and 10th of November, specifically November 3, 5, 11 and 13. They usually pour at night or in the morning.

I told him that due to an active travel schedule in November and December we would likely not be able to visit before January or February. He said that if we provide him with a window of dates in those months he might be able to schedule a pour to fit.

I asked if the heat numbers 156529 (Westinghouse WOG) and 155487 (Westinghouse Ring) could apply to more than one pipe casting. He said that the heat designations I gave him applied to only a single pipe pour. Also, he said that the 156529 heat was poured in 1978. And that the mold had a rammed sand lining 1 to 2 inches thick. Presently they use an iron mold with a thin spayed refractory coating.

I would like to establish a window of dates for the Sandusky visit as soon as possible. I will call Mike on Monday morning to see if we can do this.

Clay

Clayton Ruud
Professor Emeritus
College of Engineering
The Pennsylvania State University
And Scientist
Pacific Northwest National Laboratory
7425 E. Columbia Dr.
Spokane, WA 99212
509-893-8969 Office

Ruud, Clayton O

From: Diaz, Aaron A
Sent: Friday, September 12, 2008 9:29 AM
To: Ruud, Clayton O
Subject: FW: CCSS material
Attachments: CF8M Material.pdf

Clay -

I presume you got a copy of this? If not....here it is.

Thanks,

Aaron Diaz
Senior Staff Scientist
Applied Physics & Materials Characterization Sciences Group
Physical & Chemical Sciences Division
National Security Directorate

Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K5-26
Richland, WA 99352 USA
Tel: 509-375-2606
Mobile: 509-531-1288
Fax: 509-375-6497
aaron.diaz@pnl.gov
www.pnl.gov

From: Anderson, Michael T
Sent: Friday, September 12, 2008 8:38 AM
To: Diaz, Aaron A
Subject: FW: CCSS material

Aaron,

I meant to send this to you earlier. This is all IHI Southwest could find relative to the specimen they sent us.

From: Grady Lagleder [mailto:Glagleder@ihiswt.com]
Sent: Tuesday, August 12, 2008 11:46 AM
To: Anderson, Michael T
Subject: CCSS material

Mike,

Here's a copy of what I found. I think if the dimensions match, the second item (labeled log 808B and heat C-1207-2) is probably what you have. (No guarantees, of course)...

Grady

Message 24 of 57
Forwarded

From	Jim Lambert <jlambert@USPIPE.com> ⊕
To	'CLAYTON RUUD' <cor1@psu.edu> ⊕
Subject	**RE: Centrifugal Cast Austenitic Steel Pipe**
Date	**Thu, Sep 18, 2008 02:27 PM**
Safe View	On [Turn Off] What is "Safe View"?

Mr. Rudd:

I have dug into the archives of a few people who remember the days when our Burlington, NJ plant had a division called Industrial Productions Division (IPD) which did in fact make the austenitic stainless steel pipe for the nuclear industry. Below is a response I received from one of our field engineers who remembers it well. Hopefully, you will find some of his comments helpful. However, these processes have long since disappeared off the scene, and as discussed during our call, the Burlington plant has been decommissioned.

If I can be of further assistance, please let me know. Jim Lambert (US Pipe and Foundry)

I worked in IPD briefly as a co-op in 1965 when I was a Final Inspector and Assistant Radiographer, then again from 1972 to 1976 after a hitch in the Air Force.

A major customer at that time was called WABCO for short. It was the Westinghouse Airbrake Company, later just Westinghouse. I recall making what we called Nuclear Reactor Coolant Piping in the IPD Steel Foundry. IPD had about 200 alloys of iron and steel in the line-up, most of it melted in motor-generator set induction furnaces, although they also had a small carbon-arc furnace for larger heats. That was mothballed during my time there.

These centrifugal castings had a target weight of about 14,000 lbs and were made of an austenitic stainless steel, as you mentioned. I seem to recall they were made of 316 SS, but I'm not sure because I remember about that same time making some castings from a more exotic 347 SS.

These were high quality castings that required 100% Liquid Penetrant Testing and

100% Radiography. They were rough machined (turned, bored, and parted) in the IPD Machine Shops before testing. In the image I have of them, they were about 33" OD by 26" ID by about 45" long with about a 3 ½" wall.

I do not believe these were actual coolant pipe. I think Westinghouse bought our castings and had them forged into pipe elbows or bends for the coolant piping system, which, of course, was all welded.

Understandably, these castings were considered critical parts of a nuclear power plant, so we went to great pains to make them good. In trying to cut down on the boring detail I will say that we had three sizes of horizontal spinners, small, intermediate, and large. The Westinghouse castings were made on one of two large spinners that were specially overhauled to run extremely smoothly. Prior to tap out, the mold was brought to casting speed and the set up was checked with a vibration meter. If the amplitude of vibration could not be maintained below a certain amount, the cast was aborted. I was told that excess vibration affected grain size in the casting, which in turn affected weldability.

As for the actual manufacturing process, IPD had three MG sets driving induction furnaces. The two larger sets normally had one 4,000 lb and one 2,000 lb furnace each, but the 4,000 lb could be swapped out for a 5,000 lb unit if required. The smaller MG set normally had two 1,000 lb furnaces. The range of casting size ran from about 30 lbs up to a maximum of about 17,000 lbs. (This was done by combining the heats from all six furnaces into one bull ladle, or occasionally two which were poured simultaneously from each end of the mold.) Pouring temperature for a large 300-series stainless steel alloy would have been around 2750°F.

All of the tubular or roll products were "flat-cast", meaning the molds were level horizontally, not pitched like a DeLavaud casting machine. Metal was poured into the mold through a "horn gate" which was like a funnel with a curved spout. This means that the metal had to run down the whole length of the mold instead of being laid in a ribbon as is done using a trough on a DeLavaud machine.

Heated molds were sprayed with a coating made of diatomaceous silica flour, bentonite, and water. The heat of the mold evaporated the water leaving a relatively hard "tooth" that provided traction for the molten metal. The mold coating was applied in multiple passes until a thickness of approximately 0.10" was achieved. This is very like the Large Diameter Casting Process used at the Bessemer Plant. In fact, when I worked in R & D in early 1965, we made the first 48" centrifugally cast ductile iron "casting" (it was a pipe without a bell) using a stationary mold and a ladle/trough car moving on rails. This process was refined and became our LD process at Bessemer ten years later.

I suspect this is more information than you wanted or needed, but I haven't thought about this stuff in years so I figured I'd better record it while I still can. I have spoken with the last President of IPD and the last Production Control Supervisor within the last year. They are both in their late seventies. If there are any other details you might be looking for, I could call them to see what they remember.

From: CLAYTON RUUD [mailto:cor1@psu.edu]
Sent: Wednesday, September 17, 2008 3:32 PM
To: jlambert@uspipe.com
Cc: aaron.diaz@pnl.gov; Michael.Anderson@pnl.gov
Subject: Centrifugal Cast Austenitic Steel Pipe

Jim, attached is a summary description of the subject project. I will re-investigate whether or not US Pipe did indeed supply austenitic stainless steel pipe to Westinghouse.

It was a pleasure talking to you.

Clay

Clayton Ruud
Professor Emeritus
College of Engineering
The PennsylvaniaStateUniversity
And Scientist
Pacific Northwest National Laboratory
7425 E. Columbia Dr.
Spokane, WA99212
509-893-8969 Office
509-434-8545 Cell

From	"Rishel, Rick D" <risheird@westinghouse.com> ⊕
To	CLAYTON RUUD <cor1@psu.edu> ⊕
Subject	RE: Discrepancy Regarding WOG ONP Specimens
Date	Tue, Sep 9, 2008 04:53 PM
CC	aaron.diaz@pnl.gov ⊕ , Michael.Anderson@pnl.gov ⊕ , "Kurek, David" <kurekd@westinghouse.com> ⊕
Safe View	On [Turn Off] What is "Safe View"?

Clay,

Mr. Kim had a memory lapse. However in looking through his report more carefully I note that in Appendix A: Grain Structure under the ONP Samples the piping side of the samples is identified as Centrifugally Cast Pipe Heat No. 156361. I also note that the grain structure is more representative of centrifugally cast pipe (i.e. columnar grains in distinct layers) than a static casting. The heat number is representative of a Sandusky product (pipe) rather than an ESCO product (elbow); the heat number is identical to that identified in Table 4.2-1 where the material is labeled "ELBOW". Table 3.0-1 in the report identifies that a 29" ID centrifugally cast pipe from Sandusky was available within Westinghouse for this project; however the only samples that are 29" ID are the INE and ONP sample sets. The ONP designation was intended to signify "Outlet Nozzle to Pipe" whereas INE was intended to signify "Inlet Nozzle to Elbow".

My conclusion: the material attached to the safe end for the ONP samples is centrifugally cast pipe and the designation "ELBOW" in Table 4.2-1 is in error.

Rick

From: CLAYTON RUUD [mailto:cor1@psu.edu]
Sent: Tuesday, September 09, 2008 2:38 PM
To: Rishel, Rick D
Cc: aaron.diaz@pnl.gov; Michael.Anderson@pnl.gov
Subject: Discrepancy Regarding WOG ONP Specimens

Rick, please recall our email correspondence last month about the discrepancy between the description of the WOG ONP specimens in the NRC reports and the information you sent me. Have you been able establish the foundry and heat for the components, especially the CCSS pipe? Following is the text from the emails:

To Clay from Rick on August 20 4:39 pm PDT:

From	"Rishel, Rick D" <rishelrd@westinghouse.com> ⊕
To	CLAYTON RUUD <cor1@psu.edu> ⊕
Subject	**RE: WOG OPE Series Pipe from US Pipe**
Date	**Thu, Sep 18, 2008 09:49 AM**
CC	"aaron.diaz@pnl.gov" <aaron.diaz@pnl.gov> ⊕ , "Michael.Anderson@pnl.gov" <Michael.Anderson@pnl.gov> ⊕
Safe View	**On** [Turn Off] What is "Safe View"?

Clay,

First regarding your question on OPE:

For the OPE series I used the WCAP-11998 report and I inferred that Heat No. C2291A was U.S. Pipe because there was no direct link between two tables in the report and the microstructures in the back. The microstructure clearly depicts a cast SS and is labeled Heat No. C2291A. Table 4.2-1 in the report lists for the OPE Series Pipe - SA351/CF8A, Heat No. C2291A, 27.5"ID. Table 3.0-1 lists the 27.5"ID cast pipe available to Westinghouse as being from U.S. Pipe; the only other 27.5"ID pipe available was forged SS.

On the other question:

Mr. Kurek has dug up a number of material certifications of material used in current Westinghouse plants that states on U.S. Pipe and Foundry Company (Industrial Products Division, Burlington, New Jersey) letterhead that SA351-CF8M pipe material was supplied. These are mostly dated in the 1971/1972 timeframe. Whereas the Heat Number C2291A is not on any of the certs we were able to find one that followed a similar heat no. naming convention, i.e. C####A.

A concern that I have to what is listed in the report is whether the CF8A designation is correct. Of all the material certs pulled by Mr. Kurek only CF8M is listed on U.S. Pipe sheets; the Sandusky certs indicate CF8M.

Rick

Appendix G

Copies of Available Composition and Ferrite Content

Appendix G

Copies of Available Composition and Ferrite Content

Page G.2 is a copy of a selected portion of Table 1 in Chopra and Chung (1985). The cast components P1 through P4 are CCSS and C1 is SCSS. Chopra and Chung (1985) describes the grain structure in C1 as banded, with both columnar and equiaxed grains with the columnar showing an axial orientation near the ends. They described the grain structures in P1 and P2 as containing equiaxed grains across the entire thickness of the pipe, while P3 and P4 contained radially oriented columnar grains. However, P3 also contained an approximately 4-mm-thick band of small equiaxed grains near the ID.

Page G.3 is a copy of a selected portion of Table 1 in Chopra (1991). Under "Reactor Components" the same heat designations are used as in Chopra and Chung (1985) but the composition values are slightly different as are the Ferrite Contents. Nevertheless, it is assumed that specimens (heats) with the same designation are the same in both reports. Chopra and Chung (1985) lists only measured ferrite at the OD and ID, while Chopra (1991) gives both measured and calculated but does not indicate the location. Chopra (1991) provides the method of calculation in terms of Hull's equivalent factors as shown below:

$$Cr_{eq} = Cr + 1.21(Mo) + 0.48\ (Si) - 4.99 \text{ and}$$
$$Ni_{eq} = (Ni) + 0.11(Mn) - 0.0086\ (Mn)^2 + 18.4\ (Ni) + 24.5\ © + 2.77,$$

where composition is in wt%. Nitrogen (N) is assumed to be 0.04 if not otherwise available. Then the ferrite content is calculated as,

$$\text{Delta Ferrite} = 100.3\ (Cr_{eq}/Ni_{eq})^2 - 170.72\ (Cr_{eq}/Ni_{eq}) + 74.22.$$

G.1 References

Chopra OK. 1991. *Estimation of Fracture Toughness of Cast Stainless Steel During Thermal Aging in LWR Systems*. NUREG/CR-4513, ANL-90/42, R2, U.S. Nuclear Regulatory Commission, Washington, D.C.

Chopra OK and HM Chung. 1985. *Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems – Annual Report October 1983 – September 1984*. NUREG/CR-4204, ANL-85-20, U.S. Nuclear Regulatory Commission, Washington, D.C.

Table 1. Product form, chemical composition, ferrite content, and kinetics of thermal embrittlement for various heats of cast stainless steel

		Chemical Composition (wt.%)							Ferrite Content[a] (%)		Impact Energy	Constant	Activation Energy
Heat	Grade	Mn	Si	Mo	Cr	Ni	N	C	Calc.	Meas.	(J/cm²)	θ	(kJ/mole)
						Keel Blocks[b]							
50	CF-3	0.60	1.10	0.33	17.89	9.14	0.079	0.034	3.0	4.4	231	-	-
49	CF-3	0.60	0.95	0.32	19.41	10.69	0.065	0.010	4.4	7.2	183	-	-
48	CF-3	0.60	1.08	0.30	19.55	10.46	0.072	0.011	5.1	8.7	213	-	-
47	CF-3	0.60	1.06	0.59	19.81	10.63	0.028	0.018	8.4	16.3	229	2.35	187
52	CF-3	0.57	0.92	0.35	19.49	9.40	0.052	0.009	10.3	13.5	247	-	-
51	CF-3	0.63	0.86	0.32	20.13	9.06	0.058	0.010	14.3	18.0	217	3.00	221
58	CF-8	0.62	1.12	0.33	19.53	10.89	0.040	0.056	3.2	2.9	286	-	-
54	CF-8	0.55	1.03	0.35	19.31	9.17	0.084	0.063	4.1	1.8	187	-	-
57	CF-8	0.62	1.08	0.34	18.68	9.27	0.047	0.056	4.4	4.0	189	-	-
53	CF-8	0.64	1.16	0.39	19.53	9.23	0.049	0.065	6.3	8.7	191	-	-
56	CF-8	0.57	1.05	0.34	19.65	9.28	0.030	0.066	7.3	10.1	206	-	-
59	CF-8	0.60	1.08	0.32	20.33	9.34	0.045	0.062	8.8	13.5	227	3.12	229
61	CF-8	0.65	1.01	0.32	20.65	8.86	0.080	0.054	10.0	13.1	250	-	-
60	CF-8	0.67	0.95	0.31	21.05	8.34	0.058	0.064	15.4	21.1	196	2.95	227
62	CF-8M	0.72	0.56	2.57	18.29	12.39	0.030	0.063	2.8	4.5	228	-	-
63	CF-8M	0.61	0.58	2.57	19.37	11.85	0.031	0.055	6.4	10.4	245	3.20	119
66	CF-8M	0.60	0.49	2.39	19.45	9.28	0.029	0.047	19.6	19.8	221	3.02	203
65	CF-8M	0.50	0.48	2.57	20.78	9.63	0.064	0.049	20.9	23.4	222	2.93	191
64	CF-8M	0.60	0.63	2.46	20.76	9.40	0.038	0.038	29.0	28.4	200	2.75	156
						76-mm Slabs[c]							
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[CHO91] Chopra, O. K., "Estimation of Fracture Toughness of Cast Stainless Steel During Thermal Aging in LWR Systems", NUREG/CR-4513, ANL-90/42, R2, June 1991.

						Reactor Components[d]							
P3	CF-3	1.06	0.88	0.01	18.89	8.45	0.168	0.021	2.8	1.9	300	-	-
P2	CF-3	0.74	0.94	0.16	20.20	9.38	0.040	0.019	12.5	15.6	386	-	-
I	CF-3	0.47	0.83	0.45	20.14	8.70	0.032	0.021	19.6	17.1	180	-	-
C1	CF-8	1.22	1.18	0.65	19.00	9.37	0.040	0.039	7.8	2.2	60	-	-
P1	CF-8	0.59	1.12	0.04	20.49	8.10	0.057	0.036	17.6	24.1	228	2.38	249
P4	CF-8M	1.07	1.02	2.05	19.64	10.00	0.151	0.040	5.9	10.0	227	2.95	143
205	CF-8M	0.93	0.63	3.37	17.88	8.80	-	0.040	21.0	15.9	272	-	-
758	CF-8M	0.91	0.62	3.36	17.91	8.70	-	0.030	24.2	19.2	270	-	-
						Service Aged[e]							
KRB	CF-8	0.31	1.17	0.17	21.99	8.03	0.038	0.062	27.7	34.0	232	2.30	-

[a] Calculated from the composition with Hull's equivalent factor.
Measured by ferrite scope AUTO Test FE, Probe Type FSP-1.
[b] *Static Cast Keel Blocks:* Foundry ESCO; Size 180 x 120 x 90–30 mm.
[c] *Static Cast Slabs:* Foundry ESCO; Size 610 x 610 x 76 mm.
[d] *Centrifugally Cast Pipes:*
P3 Foundry SANDUSKY; Size 580 mm O.D., 76 mm wall.
P2 Foundry FAM, France; Size 930 mm O.D., 73 mm wall.
P1 Foundry ESCO; Size 890 mm O.D., 63 mm wall.
P4 Foundry SANDUSKY; Size 580 mm O.D., 32 mm wall.
205 Size 305 mm O.D., 25 mm wall.
Static Cast:
Elbow 758: Size 305 mm O.D., 30 mm wall.
Pump Impeller I: Foundry ESCO; Size 660 mm diameter.
Pump Casing C1: Foundry ESCO; Size 600 mm O.D., 57 mm wall.
[e] *KRB Reactor Pump Cover Plate:* Foundry GF; Size 890 mm diameter.

TABLE 1. (Contd.)

Heat	Grade	Composition,[a] wt % Mn	Si	Mo	Cr	Ni	N	C	Location	Hardness, R_B	Ferrite Content,[b] %
66[c]	CF-8M	0.71	0.60	2.36	19.41	9.13	0.030	0.060	Row 3	84.6	19.2
									Row 6	85.8	20.5
65		0.66	0.63	2.53	20.95	9.39	0.060	0.060	Row 3	88.4	21.4
									Row 6	89.5	25.4
64[c]		0.70	0.71	2.41	20.87	9.01	0.030	0.050	Row 3	89.7	27.5
									Row 6	89.7	29.3
					Cast Components						
C1	CF-8	1.22	1.19	0.64	19.10	9.32	0.041	0.036	O.D.	78.3	2.3
					18.89	9.42			I.D.	80.6	1.7
P1	CF-8	0.56	1.07	0.04	20.38	8.00	0.053	0.032	O.D.	84.5	27.6
					20.60	8.20			I.D.	85.3	19.5
P3	CF-3	1.04	0.86	0.01	18.93	8.33	0.159	0.020	O.D.	80.6	2.5
					18.85	8.56			I.D.	83.7	0.9
P2		0.72	0.92	0.16	20.20	9.24	0.041	0.020	O.D.	82.4	15.9
					20.20	9.51			I.D.	85.1	13.2
I		0.46	0.80	0.44	20.08	8.50	0.030	0.016	Vane 3	81.1	20.2
					20.20	0.80			Vane 1	82.2	14.3
					20.34	8.64			Shroud	78.1	16.9
					20.20	8.84			Hub	81.0	19.1
P4	CF-8M	1.07	1.02	2.06	19.63	10.00	0.153	0.039	O.D.	83.0	11.1
					19.65	9.99			I.D.	83.2	9.8

[a] Chemical composition of the keel blocks supplied by the vendor.
[b] Ferrite content measured by Ferrite Scope, Auto Test FE, Probe Type FSP-1.
[c] Chemical composition of the large experimental heats.

[CHO85] Chopra, O. K. And Chung, H. M., Long-Term Embrittlement of Cast Duplex Stainless Steels in LWR Systems-Annual Report October 1983 - September 1984", NUREG/CR-4204, ANL-85-20, March 1985.

Appendix H

Sandusky Foundry and Machine Co. and ESCO Heats Used in WOG Specimens APE and MPE

Appendix H

Sandusky Foundry and Machine Co. and ESCO Heats Used in WOG Specimens APE and MPE

SANDUSKY CENTRIFUGAL CASTINGS
FOUNDRY & MACHINE CO.

TWX: 810-492-2624
TELEX: 980-563

SANDUSKY, OHIO
44870

PHONE: (419) 626-5340
CABLE: SANCAST

Documentation Package #9-SFP

Westinghouse Purchase Order #546-CVH-215913-VM

Size: 31" I.D. x 2-1/2" wall x 100" long

Items covered:

Quantity	W Item No.	SFM Heat No.	SFM Shop Order
2	003	156529 - Pc. 1 & 2	21812

Section A

Laboratory tests were performed on Heat No. 156529 with the following results which conform to ASME Section II 1974, with Winter 1974 Addenda Material Specification SA351 Grade CF8A not hydrotested.

1. Chemical Analysis, %

0.05	Carbon	8.3	Nickel
0.66	Manganese	0.032	Phosphorus
1.10	Silicon	0.020	Sulphur
20.0	Chromium	0.02	Cobalt

2. Mechanical Test, Transverse

Yield Strength, psi 0.2% offset	42,000
Tensile Strength, psi	82,800
Elongation, % in 2"	42.5

G. J. Deffenbaugh
Laboratory Manager

Date 4-12-78

Order 546-CVH-215913 -VN Spin SFP-RCFCCP Serial 156529

EACO CORPORATION

MATERIAL TEST REPORT

48-03547-73

CUSTOMER: WESTINGHOUSE	ITEM 31" ID x 40° Elbow	HT. NO. 28594 -3
S.O. J6676197 P.O.	PATTERN X10421B	SERIAL NO.

MTL. SPEC. ASME SA351 GR CF8A -Section II 1977 Edition with addenda through Summer 1977

MECHANICAL PROPERTIES

YIELD STR. 0.2% OFFSET PSI	35,550	
ULTIMATE TENSILE STR. PSI	83,000	
ELONG. IN 2 INCHES – PERCENT	66	
REDUCTION OF AREA – PERCENT	76	
HARDNESS – BRINELL		
HARDNESS – ROCKWELL		
IMPACT FT. LBS. – CHARPY		

CHEMICAL ANALYSIS

CARBON	MANGANESE	SILICON	CHROMIUM	NICKEL	MOLYBDENUM	COPPER	SULPHUR	PHOSPHORUS	COBALT	FERRITE*	
.03	.86	1.20	20.03	8.66			.007	.020	.07		

Acidified copper sulfate test for intergranular corrosion (Strauss)
No. specimens tested Degree of bend
Results: Satisfactory (no cracking) Unsatisfactory (cracking)

Boiling nitric acid test (Huey)
Corrosion loss: I.P.M. I.P.Y.

Weldability bend test: Degree Results

REMARKS: *Ferrite calculated by Schoefer modification of the Schaeffler diagram.

Applicable Code Case N-181

REVIEWED BY:

We certify that the foregoing is a true and correct report of the values obtained and that they comply with the requirements of the specification unless noted otherwise.

[signature]
QUALITY ASSURANCE REP.

10/4/78
DATE

Appendix I

Delta Centrifugal Visit Notes

Appendix I

Delta Centrifugal Visit Notes

PNNL/EPRI Visit to Delta Centrifugal, May 21, 2009
Temple, Texas; 888-430-3100; 254-773-9055

Delta Centrifugal Personnel:
Mark A. Anderson, Executive Vise President, Manderson@DeltaCentrifugal.com
Robert T Rose, CEO, President, rrose@deltacentrifugal.com
Roman Radon, Technical Director, rradon@deltacentrifugal.com
Rod Nicholson, Sales Manager, Rnicholson@deltacentrifugal.com

EPRI Personnel:
Douglas Kull, Sr., Project Engineer, Charlotte, NC, 704-595-2172, dkull@epri.com

PNNL Personnel:
Aaron, Diaz, Staff Scientist, Richland, WA, 509-375-2606, aaron.diaz@pnl.gov
Clayton O. Ruud, Scientist, Spokane, WA, 509-893-8969, cor1@psu.edu

The visit commenced at 9:00 am, with nearly one and a half hours of discussion, much of it in the form of questions about centrifugal casting practices at Delta and other foundries. M. A. Anderson stated that he had been at Delta since 1977, and previously at a foundry in the Los Angles area. He mentioned that Delta casts a number of stainless steel alloys including austenitic and PH, as well as nickel alloys. He asked if we were familiar with Sandusky, Wisconsin Centrifugal, and American Cast Iron and Pipe Co.–ACIPCO (now called American Centrifugal) in Birmingham, Alabama. He mentioned a Mike Fenton (Sales Engineer) with Sandusky who might be helpful in our attempts to coordinate a meeting there. He described three types of molds used for centrifugal casting of pipe. Those being ceramic (alumina) wash (about 0.01-in. thick), ceramic lining (up to 3-in. thick), and a rammed sand lining. These various types are being used by Delta, American, and Sandusky, respectively.

Delta uses low-alloy steel molds (AISI 4220) cast or forged. Forged are used in diameters 16 in. and larger. They cast up to 32-in. diameter and from 30 in. to 13-ft long. The molds are spray-coated at between 500°F and 600°F with a mold wash of alumina about 0.06-in. thick when dried, and it has an orange peel texture. The mold is about 300°F when pouring is initiated. Some castings (e.g., nickel alloys) are poured with an argon cover, but argon-oxygen decarburization (AOD) is not applied in Delta's process.

To initiate pouring, the mold is held horizontally and spun at about 100 Gs (~500 rpm for a 30-in. ID mold) during the entire pour. They maintain a fairly constant blend rate but may "slightly" slow the rotation rate after the casting begins to solidify. The molds and spinners are balanced to reduce vibration to a maximum of 0.01 in. in amplitude. No rubber or other material is used to dampen spinner support/frame structures from vibration. Delta's experience is that rubber pads only exacerbate vibration and that controlling vibration by balancing the trunyan spinners is more effective. Delta uses a hand-held vibration meter (transducer) to measure vibration and maintain vibration to less than 10 mils. The spout is not kept at any certain angle, but rather configured horizontally. The spout of a pouring basin is inserted into an orifice in one of the end caps and the molten metal is poured into the pouring basin from a ladle. A large amount of melt is poured at the beginning to quickly run metal to the opposite end of the mold, and the temperature difference from end-to-end is between 25° and 50°F. The pour from start to finish lasts about 1.5 minutes and the casting solidifies within 5 to 8 minutes. The rate of solidification is enhanced by an atomized mist of water sprayed on the outside of the mold after pouring and during solidification. Pouring temperatures for AISI 304 and 316 (ASTM CF 8, 8A, and 8M) are typically 2800°F, and for heavy-walled castings temperatures about 50°F higher are used.

According to M. A. Anderson, vibration leads to equiaxed grains. Typically Delta's castings tend to produce bands of equiaxed to columnar to equiaxed from OD to ID. He looked at the WOG ONP grain structure as columnar, whereas C. O. Ruud had judged it as equiaxed. This observation revealed the need to establish classifications for grain structure for the project. Delta typically machines about ¼ inch from the OD and ½ inch from the ID of their castings. He mentioned that the grain structure that might be observed depends on whether the end or the middle of the pipe is being examined.

M. A. Anderson asked if there was a concern about stress corrosion cracking (SCC) and ferrite content and C. O. Ruud knew of no such concern. According to Griesbach et al. (2007), ferrite improves the corrosion resistance as well as sensitization behavior of cast stainless steel. However, ferrite also produces detrimental effects such as thermal embrittlement and toughness degradation. M. A. Anderson mentioned that in his experience, there is a direct correlation between increased levels of delta ferrite and the formation of columnar (dendritic) gains, also increased delta ferrite increases the strength of the alloy. Nevertheless, Temple and Ogilvy (1992) hypothesized that lower ferrite is likely to yield totally columnar grain structures in statically cast stainless steel components.

C. O. Ruud asked how they measured delta ferrite, and M. A. Anderson mentioned estimation by the Schoefer modification to the Schaeffler diagram, Severin magnetic pull test, and the Ferris scope. When we toured their laboratory, we were shown the magnetic pull test device.

Upon touring the casting facility, we witnessed the pouring of short (about 30 or 40-in. long) cylinders less than 12 in. in diameter, although Delta is capable of pouring much longer lengths and larger diameters.

The Delta Centrifugal visit was informative and their personnel were very hospitable and open, answering our questions without hesitation. And, our host, M. A. Anderson, and the other Delta personnel offered to answer any questions we might have in the future.

References

Griesbach TJ, G Cofie and RO McGill. 2007. "An Update on Flaw Tolerance Evaluation Studies on Thermally Aged Cast Austenitic Stainless Steel Piping." In *6th International Conference on NDE in Structural Integrity for Nuclear and Pressurized Components*. October 8-10, 2007, Budapest, Hungary.

Temple JAG and JA Ogilvy. 1992. *Propagation of Ultrasonic Elastic Waves in Centrifugally Cast Austenitic Steel*. AEA-RS-4223, AEA Reactor Services.

Appendix J

Ferrite Content Measurement and Calculation

Appendix J

Ferrite Content Measurement and Calculation

Aubey et al. (1982) compared several methods of calculating and measuring ferrite in austenitic stainless steels including four computational methods based upon the elemental composition of the steel, two ferro-magnetic methods, and a metallographic point-count method. The ferro-magnetic methods included the Magne-Gage and the Feritscope. With 50 samples compared, the discrepancy between the point-count, the two measurement methods, and the two best computation methods ranged from zero to eleven percent, with a mean discrepancy of 2.4 percent. According to Ratz and Gunia (1969), the metallographic point-count method gives very consistent results and thus was selected as the standard for Aubrey et al.'s investigation.

Lundin et al. (1999) evaluated several ferrite measurement techniques for austenitic and duplex stainless steel castings. These were metallographic point counting, constitutions diagrams (calculation from composition), magnetic attraction, x-ray diffraction, Mossbauer Effect, magnetic permeability, and magnetic saturation. They did not find the metallographic point-counting technique suitable for a number of reasons including: (1) because the material was not homogeneous, the size of volume examined was not statistically relevant; (2) variations in sample preparation and examination; and (3) interpretation of the microstructure—it was destructive, and not readily field-deployable. And for various reasons, including field portability, they elected to focus on magnetic-based techniques, including magnetic, attractive force, and magnetic permeability indicators.

Magnetic indicators use a permanent magnet, suspended on a lever arm, and the specimen ferrite content is compared to that of a reference magnet. The degree to which ferrite content range could be characterized was governed by reference magnets and thus was only a "quick-and-dirty" estimation (Lundin et al. 1999). These types of devices include the Severe Gage, Tinseley Gage, and the Elcometer.

Attractive force devices correlate the force required to separate a magnet from the specimen. A permanent magnet, suspended from a lever arm, is lowered until the magnet contacts the specimen; then using a calibrated dial, torque is applied through a helical spring until the magnet separates from the specimen. The dial gage reading is then compared to a calibration curve to determine the ferrite content of the specimen. The Magne Gage is an example of this type of instrument (Lundin et al. 1999).

Magnetic permeability is defined as the ratio of magnetic induction to magnetic field strength. Ferrite measurements using this technique require that a magnetic field be induced in the specimen and the resulting field strength be measured to establish the permeability. The technique requires that the instrument is calibrated against known standards and the Feritscope is an example of a magnetic permeability instrument (Lundin et al. 1999).

J.1 References

Aubrey LS, PF Wieser, WJ Pollard and EA Schoefer. 1982. "Ferrite Measurement and Control in Cast Duplex Stainless Steels." In *Stainless Steel Castings, ASTM STP 756.* Eds: VG Behal and AS Melilli. American Society for Testing Materials, West Conshohocken, Pennsylvania.

EPRI. 1991. *Application of Electromagnetic Acoustic Transducers to Coarse-Grained Material.* EPRI NP-7438, Electric Power Research Institute, Palo Alto, California.

Lundin CD, W Ruprecht and G Zhou. 1999. *Literature Review Ferrite Measurement in Austenitic and Duplex Stainless Steel Castings,* The University of Tennessee, Knoxville, Tennessee. Submitted to SFSA/CMC/DOE.

Ratz GA and RB Gunia. 1969. "How Accurate are Methods for Measuring Ferrite?" *Metal Progress* 95(1):76–80.

Table J.1. Ferrite Calculations of Selected Specimens from Table 4.4 of this Report

Specimen	C	Mn	Si	P	S	Cr	Ni	Mo[(a)]	N[(a)]	Cr_e	Ni_e	Cr_e/Ni_e	$\%Fe_1$	$\%Fe_2$	%Fe Rprt
#1,2,6,7,14,&15 WOG -	0.05	0.66	1.1	0.032	0.02	20.0	8.3	0.5	0.04	15.54	12.36	1.257	18.1		
Ht.156529 by SFM	0.05	0.66	1.1	0.032	0.02	20.0	8.3	0.5	0.04	16.66	12.38	1.35		18.3	
#1,2,6,&7 WOG -	0.03	0.86	1.2	0.02	0.007	20.03	8.66	0.5	0.04	15.62	12.25	1.27	19.6		
Ht.28594-3 by ESCO	0.03	0.86	1.2	0.02	0.007	20.03	8.66	0.5	0.04	16.84	12.24	1.38		19.6	
#23 ANL C1 by ESCO	0.039	1.22	1.18	0.033	0.008	19.0	9.37	0.65	0.04	15.36	13.95	1.10	7.84		7.8
	0.039	1.22	1.18	0.033	0.008	19.0	9.37	0.65	0.04	16.69	14.44	1.16		8.43	2.2
#24 ANL P1 by ESCO	0.036	0.59	1.12	0.026	0.013	20.49	8.1	0.04	0.036	16.09	12.48	1.29	20.8		17.6
	0.036	0.59	1.12	0.026	0.013	20.49	8.1	0.04	0.036	17.24	12.66	1.36		19.2	24.1
#25 ANL P2 by FAM	0.019	0.74	0.94	0.019	0.005	20.20	9.38	0.16	0.04	15.85	13.43	1.18	12.5		12.5
	0.019	0.74	0.94	0.019	0.005	20.20	9.38	0.16	0.04	16.84	13.61	1.24		12.1	15.6
#26 ANL P3 by SFM	0.021	1.06	0.88	0.017	0.014	18.89	8.45	0.01	0.168	14.33	14.93	0.96	2.76		2.8
	0.021	1.06	0.88	0.017	0.014	18.89	8.45	0.01	0.168	15.23	16.23	0.94		2.1	1.9
#27 ANL P4 by SFM	0.04	1.07	1.02	0.019	0.015	19.64	10.0	2.05	0.151	17.62	16.64	1.06	5.92		5.9
	0.04	1.07	1.02	0.019	0.015	19.64	10.0	2.05	0.151	19.05	17.91	1.06		5.1	10.0
PNNL CCSS-RRT	0.06	0.68	1.17	0.02	0.02	20.42	8.58	0.5	0.04	15.99	12.89	1.24	16.8		17.4
Ht 144179 by SFM	0.60	0.68	1.17	0.02	0.02	20.42	8.58	0.5	0.04	17.19	12.97	1.33		17	17.4

NOTE: The top set of numbers in each “row” indicates results for Model #1; the bottom set of numbers in each “row” indicates Model #2 results.

#1 Model for predicting ferrite content according to Aubrey et al. (1982): Cr equivalent = Cr_e = %Cr + 1.21 %Mo + 0.48 %Si - 4.99 and Ni equivalent = Ni_e = %Ni + 0.11 %Mn - 0.0086 $\%Mn^2$ + 18.4 %N + 24.5 %C + 2.77. Ferrite Content = $\%Fe_1 = 100.3 \times (Cr_e/Ni_e)^2 - 170.72\,(Cr_e/Ni_e) + 74.22$. Note these equations are based upon Hull’s equivalent factors (Aubrey 1982).

#2 Model for predicting ferrite content according to Aubrey et al. (1982): Cr equivalent = Cr_e= %Cr + 1.4 %Mo + 1.5 %Si - 4.99 and Ni equivalent = Ni_e = %Ni + 30 %C + 0.5%Mn + 26(%N - 0.02) + 2.77. Ferrite Content = $\%Fe_2 = 55.84 \times (Cr_e/Ni_e)^2 - 87.87\,(Cr_e/Ni_e) + 35.39$.

(a) Values of Mo and N were assumed to be 0.5 and 0.04 where chemistry data for these elements were not available (EPRI 1991).

(b) Chemistry from Chopra et al. (1991).

Pacific Northwest
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY

Proudly Operated by **Battelle** *Since 1965*

902 Battelle Boulevard
P.O. Box 999
Richland, WA 99352
1-888-375-PNNL (7665)
www.pnl.gov